CTF SYSTEMS INC.

TP 7949E

FABRICATION AND TESTING OF REDUCED-SCALE SUPERCONDUCTING MAGNETS

by

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17. Abstract

This report documents the development of technology suitable for the fabrication of lightweight, high current density superconducting magnets. The long-range application of this technology is for the levitation and propulsion magnets for the Canadian electrodynamic Maglev vehicle. In addition, a number of near-term spin-off benefits have been identified flowing from this developmental effort. During the contract, the following results have been achieved:

- evaluation and selection of a suitable cryogenic grade epoxy for impregnation of tightly wound coils of solenoidal and racetrack forms;
- development of techniques for winding, epoxy impregnating and curing various coils with fill factors in excess of 80% (copper wire);
- development of techniques for fabrication of lightweight, vacuum tight coil frames of SS304L;
- establishment of a superconducting magnet test facility;
- successful fabrication and testing of a high current density superconducting solenoid.

This superconducting magnet reached the design current after one quench, and to within 1% of the short sample critical current after eight quenches. There was no evidence of quench induced damage to the coil performance.

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17. Résumé

Ce rapport fait état de la mise au point des techniques nécessaires à la fabrication d'aimants supraconducteurs légers à densité de courant élevé. A long terme, cette technologie sera appliquée aux aimants de sustentation et de propulsion du train canadien à sustentation magnétique, communément appelé MAGLEV. De plus, les recherches ont permis de mettre en évidence un certain nombre d'applications intéressantes à moyen terme. Les résultats suivants ont été obtenus:

- évaluation et choix d'une résine époxy cryogénique destinée à imprégner des bobines étroitement enroulées de forme cylindrique et ovalisée;
- élaboration de techniques d'enroulement, d'imprégnation d'époxy et de durcissement de diverses bobines dont le facteur de remplissage est supérieur à 80% (fil de cuivre);
- élaboration de techniques de fabrication de supports de bobinage légers et hermétiques en feuilles de type SS304L;
- établissement d'un poste d'essai d'aimants supraconducteurs;
- fabrication et essai d'un solénoïde supraconducteur à densité de courant élevé.

L'aimant supraconducteur a atteint son courant de fonctionnement après une transition et, à 1 % près, le courant critique mesuré sur de petits échantillons, après huit transitions. Les transitions ne semblent pas avoir nui à la performance de la bobine.

18. Mots-clés	19. Diffusion
Maglev, sustentation magnétique, aimants supraconducteurs, supports légers, courant élevé, imprégnation à la résine époxy.	Le Centre de développement des transports dispose d'un nombre limité de copies.

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SUMMARY

This report documents a research and development contract entitled "Fabrication and Testing of Reduced Scale Superconducting Magnets". The work has been sponsored by the Transportation Development Centre of Transport Canada (TDC), and has been carried out by CTF Systems Inc. of Port Coquitlam, B.C.

This research is related to the Canadian Maglev program, which is aimed at the optimal deployment of non-contact Maglev transportation technology, within the framework of Canadian requirements. The Maglev mode of interest is the electrodynamic or EDS mode which utilizes cryocooled superconducting magnets both to levitate and propel the vehicles at velocities up to 450 km/h. As this program has evolved during the past decade, TDC has recognized and supported the need to develop a reasonable level of expertise at the government, university and industrial research laboratory levels.

The goals of the present contract have been:

* establishment of procedures for impregnation of tightly wound coils of both solenoidal and racetrack geometries with suitable cryogenic grade epoxies;

* fabrication of superconducting coils using the established impregnation procedures;

* establishment of a facility for testing the fabricated superconducting coils, including a suitable cryogenic test dewar and insert, a high current power supply and suitable magnetic field measuring equipment;

* evaluation of the near-term spin-off benefits flowing from superconducting magnet and cryocooler technologies appropriate to the EDS Maglev system;

* outlining of a long range plan for development of the cryogenic components for the Canadian EDS Maglev system.

A system for vacuum impregnation of tightly wound coils has been developed and several model solenoidal and racetrack coils have been wound, impregnated and sectioned after curing the epoxy in a suitable oven system. The work was initiated with simple molds of aluminum, using round copper wire and progressed to fabrication of racetrack coils of square copper wire

in molds of welded SS 304L sheet. The racetrack coils were of levitation magnet size (106 cm long by 30 cm end diameter with a 4 cm square section). Fill factors in excess of 80% have been achieved with the final model coils, and microscopic examination of their composite sections indicated minimal void content.

After successfully establishing fabrication and epoxy impregnation procedures, a superconducting solenoid was fabricated with design strength 400 KAT, and mean diameter 30 cm. This coil was mounted on a suitably instrumented test insert in a bucket test dewar, both of which were fabricated at CTF. The system was cooled to liquid helium temperatures and the coil was energized until a quench was initiated. This procedure was repeated a number of times with different starting conditions. Sometimes the coil was recooled from LN_2 temperature (77K) and finally from room temperature. The major results for this first superconducting coil were as follows:

* the coil reached the design current after the first quench;

* the coil trained to within a few percent of the short sample critical current value;

* for most of the quench tests, $\geq$ 90 % of the total coil energy was dissipated in the windings after the quench. Using the QUENCH computer program, it was estimated that post-quench, the coil winding had been subjected without damage to peak temperatures of about 110 K, and peak internal voltages of the order of 1 kV;

* it was also estimated, that at the maximum operating current achieved during the quench tests (914 A), the winding had been subjected to a peak circumferential stress of $>$ 170 MPa. (This stress is a superposition of winding, cooldown and Lorentz stresses.)

It was concluded from these tests that the superconducting coil characteristics were very satisfactory, and that a rugged, minimal training performance had been achieved for solenoidal type coils.

During the course of the contract, two papers on this work were delivered at conferences specializing in Maglev technology:

(a) Maglev Transport '85, in Tokyo, Japan, September , 1985.
(b) Maglev and Linear Drives, Vancouver, B. C. , May, 1986.

Two reports have been prepared by CTF summarizing the applications of superconducting magnets and the associated closed cycle cryocoolers. The report on superconducting magnets outlines various applications and spin-off opportunities which are possible in the near-term and includes areas such as high energy physics and nuclear particle spectroscopy, magnetic resonance imaging, and magnetic separation.

The applications of closed cycle cryocoolers include superconducting magnets and also superconducting micro-electronics. The latter is a relatively new field which is growing at a significant rate. Applications of superconducting circuitry and devices include ultra-sensitive SQUID magnetometers, RF and microwave amplifiers and detectors, far-infrared detectors, and high speed digital and analog signal processing devices and integrated circuits. Instruments based on SQUID magnetometers are now commercially available and, in particular, the field of biomagnetism is viewed as progressing toward a relatively large market base. The development of a highly reliable, efficient, cryocooler of reasonable cost is expected to have a major impact on the viability of superconducting micro-electronic instrumentation. There have already been significant advances toward these goals in recent years.

As part of the contractual requirements, an outline long-range plan for development of cryogenic components for the Canadian EDS Maglev system has been presented to TDC. This includes the development and testing of Levitation and Linear Synchronous Motor magnets coupled to a suitable closed cycle cryocooler. After review by TDC and the National Research Council of Canada, it has been decided to pursue the magnet hardware development through a follow-on phase where a full scale levitation racetrack coil will be fabricated and tested. Accordingly, a detailed proposal for this phase has been submitted.

SOMMAIRE

Le présent rapport porte sur les faits saillants d'un contrat de recherche et développement intitulé "Fabrication and Testing of Reduced Scale Superconducting Magnets". Les travaux ont été financés par le Centre de développement des transports (CDT) de Transports Canada et effectués par CTF Systems Inc. Port Coquitlam, C.-B.

Ce projet s'inscrit dans le cadre du programme canadien MAGLEV qui vise la mise au point d'une technique optimale de transport par sustentation magnétique appropriée aux besoins canadiens. La filière retenue est celle de la répulsion électrodynamique qui consiste à utiliser des aimants supraconducteurs cryogéniques pour assurer la sustentation et la propulsion des trains à des vitesses pouvant atteindre 450 km/h. Compte tenu de l'évolution du programme au cours de la dernière décennie, le CDT a reconnu et appuyé la nécessité de porter à un niveau raisonnable la compétence et les connaissances des laboratoires de recherche du gouvernement, des universités et de l'industrie dans ce domaine.

Les objectifs du contrat étaient les suivants:

* élaboration de techniques d'imprégnation de bobines étroitement enroulées, de forme cylindrique ou ovalisée, à l'aide de résines époxy cryogéniques appropriées.

* fabrication de bobines supraconductrices suivant les techniques élaborées.

* établissement d'un poste d'essai d'aimants supraconducteurs, avec vase Dewar et chambre d'essais cryogéniques, bloc d'alimentation à courant élevé et appareils de mesure des champs magnétiques.

* évaluation des applications intéressantes à moyen terme qui découlent de l'étude des cryostats et des aimants supraconducteurs destinés au MAGLEV.

* élaboration d'un plan à long terme pour la mise au point de composants cryogéniques destinés au MAGLEV canadien.

L'équipe a mis au point un système d'imprégnation hermétique de bobines étroitement enroulées. Plusieurs bobines, de forme cylindrique ou ovalisée, ont été enroulées, imprégnées et sectionnées après durcissement

de la résine époxy dans un four spécialement adapté. On a commencé par enrouler du fil de cuivre de section ronde dans de simples moules en aluminium pour passer ensuite à la fabrication de bobines ovalisées à l'aide de fil de cuivre de section carrée dans des moules en feuilles de type SS304L soudées. Les bobines ovalisées correspondaient à la dimension des aimants de sustentation (106 cm de longueur, 30 cm de largeur aux extrémités et une section carrée de 4 cm). Sur les dernières bobines fabriquées, on a obtenu des facteurs de remplissage supérieurs à 80%, et l'examen au microscope des sections composites a révélé un pourcentage minimal de vides.

Après avoir validé notre technique de fabrication et d'imprégnation à la résine époxy, nous avons fabriqué un solénoide supraconducteur d'une capacité de 400 KAT et d'un diamètre moyen de 30 cm. Le solénoide, ayant été installé sur un support d'essai équipé des appareils de mesure requis, a été placé dans un vase Dewar. Le support et le vase ont été fabriqués sur place. Le solénoide a été ensuite refroidi à la température de l'hélium liquide et excité jusqu'à l'amorce d'une transition. L'opération a été répétée un certain nombre de fois en modifiant les conditions initiales. Pour certains essais, la bobine a été refroidie à partir de la température de LN_2 (77K) et pour les derniers, à partir de la température de la pièce. Les principaux résultats obtenus sont les suivants:

* La bobine a atteint le courant nominal de fonctionnement après la première transition.

* La bobine a été amenée par traînage à quelques pour-cents près du courant critique mesuré sur de petits échantillons.

* Pour la plupart des essais de transition, ≥ 90% de l'énergie totale de la bobine était dissipée dans le bobinage, après la transition. Grâce au programme informatique QUENCH, on a pu établir qu'en période post-transitoire, le bobinage était soumis, sans dommage, à des températures de crête d'environ 110 K et des tensions internes de crête de l'ordre de 1kV.

* Les essais ont également permis d'établir qu'au courant de fonctionnement maximum obtenu pendant les essais de transition (914 A), le bobinage avait été soumis à une contrainte circonférentielle de > 170 MPa (cette contrainte étant une superposition des contraintes dues à l'enroulement, au refroidissement et aux effets de Lorentz).

Les essais ont permis de conclure que la bobine supraconductrice présentait des caractéristiques très satisfaisantes et que le type solénoide

affichait une bonne résistance aux transitions, ne nécessitant qu'un traînage minimal.

Au cours de l'exécution du contrat, deux documents portant sur nois travaux ont été présentés à des conférences consacrées à la technologie de la sustentation magnétique:

(a) Maglev Transport '85, Tokyo, Japon, septembre 1985.

(b) Maglev and Linear Drives, Vancouver, C.B., mai 1986.

Le CTF a préparé deux rapports qui résument les diverses applications des aimants supraconducteurs et des cryostats en circuit fermé. Le rapport sur les aimants supraconducteurs expose les diverses applications et les possibilités intéressantes à moyen terme, notamment dans les domaines suivants: physique des hautes énergies et spectroscopie nucléaire, imagerie par résonnance magnétique et séparation magnétique.

Les applications relatives aux cryostats en circuit fermé comprennent les aimants supraconducteurs et la micro-électronique supraconductrice. Cette dernière constitue un domaine relativement récent dont les applications suscitent un intérêt marqué. Les applications des circuits et des dispositifs supraconducteurs comprennent les magnétomètres SQUID ultra-sensibles, les amplificateurs et les détecteurs RF et hyperfréquences, les détecteurs à infrarouge éloigné ainsi que les dispositifs rapides de traitement des signaux analogiques et numériques et les circuits intégrés. Des instruments dérivés des magnétomètres SQUID sont désormais accessibles sur le marché. D'ailleurs, c'est le domaine du biomagnétisme qui semble offrir les meilleurs perspectives de marché. La mise au point de cryostats très fiables, efficaces et peu coûteux devrait nettement favoriser le développement des appareils à circuits micro-électroniques supraconducteurs. Ce secteur a déjà enregistré des progrès importants au cours des dernières années.

Dans le cadre du contrat, les grandes lignes d'un projet à long terme visant la mise au point de composants cryogéniques destinés au Maglev canadien ont été soumises au CDT. Il s'agissait entre autres de la mise au point et de l'essai d'aimants de sustentation et de moteurs linéaires synchrones couplés à un cryostat approprié en circuit fermé. Après étude du projet par le CDT et le Conseil national de recherches du Canada, il a été décidé de poursuivre la mise au point des aimants et de procéder à la fabrication et à l'essai d'une bobine de sustentation ovalisée, vraie grandeur. A cette fin, nous avons soumis un projet détaillé de cette phase.

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1. INTRODUCTION

1.1 Background

This project is part of the Canadian Maglev program, which is a long range R. & D. effort aimed at the optimal deployment of non-contact transportation technology within the framework of Canadian requirements. A recent overview presented at the Maglev Transport '85 conference in Tokyo, outlines the objectives and status of the Canadian program by mid-1985 [1, Appendix A][1]. The choice of the electrodynamic Maglev mode using superconducting magnets (EDS) has been primarily dictated by operation under the extremes of Canadian winter conditions, and the potential for much reduced guideway capital and maintenance costs. A principal objective of this program up to the present time has been the definition, refinement and economic evaluation of an appropriate EDS Maglev system. It was recognised during the 1970's that the deployment of a revenue Maglev system may not be feasible in the proposed Toronto-Ottawa-Montreal corridor until the early years of the 21st century. The strategy adopted has been to maintain a modest level of research and development in this technology in order to gain the expertise necessary to exploit Maglev when the need becomes apparent, and in the expectation of near-term spin-off benefits to transportation and other emerging technologies.

The historical evolution of the Canadian program is outlined in Table 1.1. In recent years, emphasis within the program has shifted towards development of critical cryogenic components. In particular, two technologies have been identified as requiring considerable further development:

(a) stable, lightweight, superconducting magnets;
(b) ultra-reliable, lightweight, efficient, closed-cycle cryocooler systems (including non-contaminating helium compressors).

This contract is related to area (a) involving the development of fabrication methods for high strength, lightweight, superconducting magnets suitable for the purposes of levitation and propulsion of the Maglev vehicle.

[1]Numbers in brackets [ ] denote references listed at the end of the report

Table 1.1 Canadian EDS Maglev Program Historical Perspective

Year	Activity	Participants
1968	Conception of Canadian Maglev program	Ferranti-Packard
	Preliminary design and analysis completed	
1970	Foundation of CIGGT at Queen's University	Queen's U.
	Formation of Canadian Maglev group	Toronto U.
	Test facility concept developed	McGill U.
	Detailed analysis and design of sub-systems	CIGGT
1972		
	Test Wheel design completed	CIGGT
1974	Test Facility fabricated and commissioned	CIGGT
	LSM propulsion demonstrated and tested	CIGGT
	LSM tests completed and control modes evaluated	CIGGT
1976	Electrodynamic suspension tests completed	CIGGT
	Detailed system conceptual design initiated	NRC
	Engineering studies of Maglev system completed	NRC/CIGGT
	Economic assessment initiated CIGGT	
1978	Modelling of levitation coil moments and forces	McGill U.
	Economic assessment completed	CIGGT
	Industrial particiption initiated	CTF Systems Inc.
1980	Isochoric cooling study completed	CTF Systems Inc.
1982	Vehicle design concept revised	NRC
	Levitation magnet design study completed	CTF Systems Inc.
1984	Technical assessment completed	NRC
	Superconducting magnet development initiated	CTF Systems Inc.
	Los Angeles-Las Vegas technology assessment initiated	CIGGT/NRC

In the following section of this chapter, the contract objectives are outlined. The subsequent chapters detail the following:

Chapter 2: Epoxy Impregnation Studies.
Chapter 3: Test Facility Preparation
Chapter 4: Superconducting Solenoid Fabrication
Chapter 5: Superconducting Solenoid Testing
Chapter 6: Analysis of Data
Chapter 7: Conferences
Chapter 8: Planning and Near-term Spin-off Benefits
Chapter 9: Conclusions .

1.2 Contract Objectives and Work Plan

The detailed statement of work from the DSS contract # OSB84-00369 is reproduced in Table 1.2, and this was utilized to generate a work plan and cash flow schedule. An outline of the work plan is displayed in Fig.1.1 with starting date August 29/1984 and delivery date March 21/1986. A significant feature of the contract was the requirement for investigation of near term spin-off benefits flowing from Maglev related hardware developments as well as a review of long range plans. These are discussed in chapter 8.

Table 1.2 DSS Contract Statement of Work (DSS serial No. OSB84-00369)

5. DETAILED STATEMENT OF WORK

5.1 Develop a detailed work plan, activity schedule, cash flow projection, project management control and documentation procedures within three (3) weeks of effective commencement date.

5.2 Participate actively in the identification and preparation of a program for the development of Canadian expertise and industrial capability in superconducting magnets and associated cryogenics. The other participants will involve TDC, NRC and other Government organizations. The plan will address immediate and long-term goals in all aspects related to superconductivity and cryogenics.

5.3 Investigate various epoxy impregnation techniques using test specimens to identify satisfactory techniques for producing superconducting coils.

5.4 Fabricate, purchase, or borrow an appropriate test Dewar.

5.5 Fabricate representative samples for tests.

5.6 Test impregnated specimens to verify suitability.

5.7 Modify and retest to identify specific performance characteristics.

5.8 Prepare facilities to accommodate test requirements.

5.9 Fabricate, test, modify and characterize appropriate sample superconducting solenoids.

5.10 Analyse the tests results.

5.11 Document the various techniques considered and recommendations.

5.12 Prepare a report.

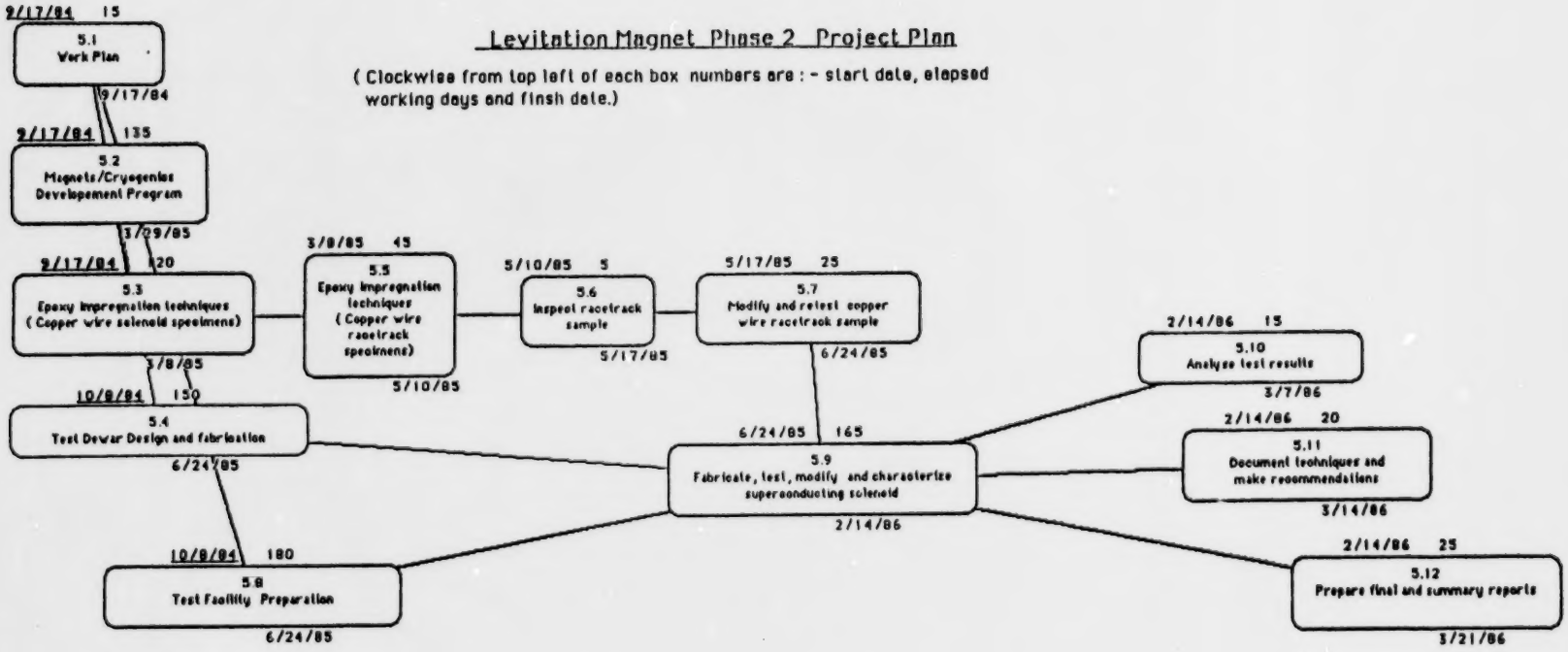


Figure 1.1 Levitation Magnet Phase 2 Project Plan

2. EPOXY IMPREGNATION

A critical objective for the contract has been to develop suitable techniques for impregnating tightly wound superconducting wire coils. Since superconducting wire is rather expensive (at least ten times the cost of copper wire with the same section), the approach adopted has been to fabricate and impregnate model coils using insulated copper magnet wire of appropriate size and geometry. A description follows of the impregnation parameter optimization together with results from fabrication of model coils with solenoidal and racetrack geometries.

2.1 Epoxy Impregnation Parameter Measurements

After reviewing all the available information for suitable epoxies, several samples were acquired for tests. Tests of interest for these samples included:

a) Mixing and handling characteristics.
b) Viscosity as a function of temperature.
c) Working (pot life) at various temperatures.
d) Cure schedule.

Viscosity as a function of temperature and time, and epoxy mix pot life at various temperatures were determined for samples at different stages of the cure cycle. The viscosity at a given temperature was determined from Stoke's law by measuring the terminal velocity of spheres falling through the epoxy mix under gravity. Examples of data for a Ciba-Geigy epoxy mix are plotted in Figure 2.1, indicating almost two orders of magnitude reduction in viscosity as the temperature is increased between 20C and 100C. In practice, the cure temperature cannot be too much higher than 100C, since the Formvar wire insulation can be damaged by excess heat.

Viscosity as a function of time at various temperatures yields the working pot life, which is critical to good impregnation in the complicated narrow channel geometry of a wire coil. The problem is more important for the racetrack geometry than the solenoidal case, due to the increased path length. Viscosity vs. time is indicated in Figure 2.2 and demonstrates that there is an optimum temperature for maximum penetration into the windings. For the present epoxy mix, this optimum temperature was estimated to be 85± 5C.

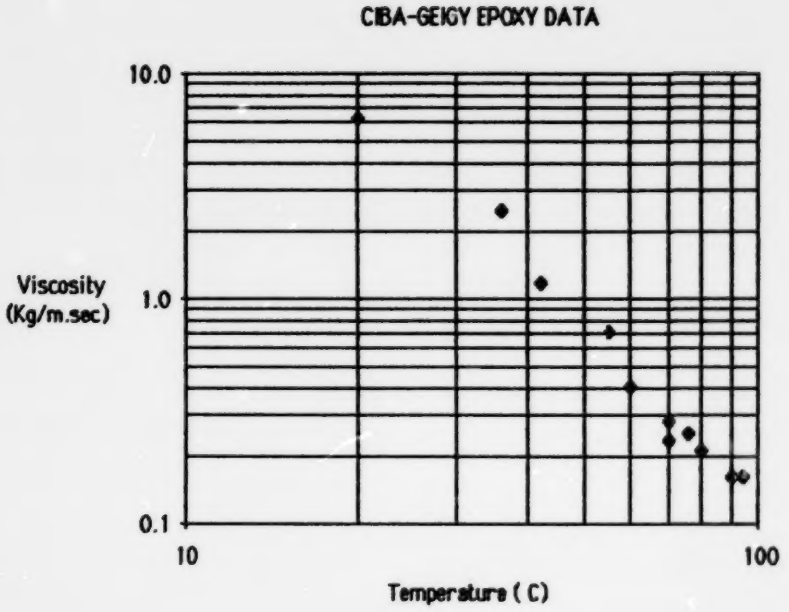


Figure 2.1 : Viscosity vs temperature for Ciba-Geigy Resin 6010 (100 pbw), and Hardener 906 (80 pbw). Each batch was measured about 10 minutes after mixing i.e. well before the trigger point.

2.2 Impregnation Oven and Procedures

Due to the nature of the epoxy adopted for impregnating the coils, the oven system which has been developed plays a central role in the impregnation procedure. The system has been assembled by coupling two commecial ovens together (Figure 2.3). Thermistors with sensitivity ±0.5C were used to map temperature profiles within the curing space for various settings of the heater controls. The thermistors indicated that even though there were local temperature variations of ± 5C, the coil+mold temperatures remained within ± 1C after thermalization to given electrical heater settings. The large heat capacity of the coil + mold acted as a thermal filter for the time-stepped heater input.

After a number of experiments, the arrangement of Figure 2.3 was adopted, since it resulted in the best control of the process. This differed from some earlier arrangements where the epoxy reservoir was heated in

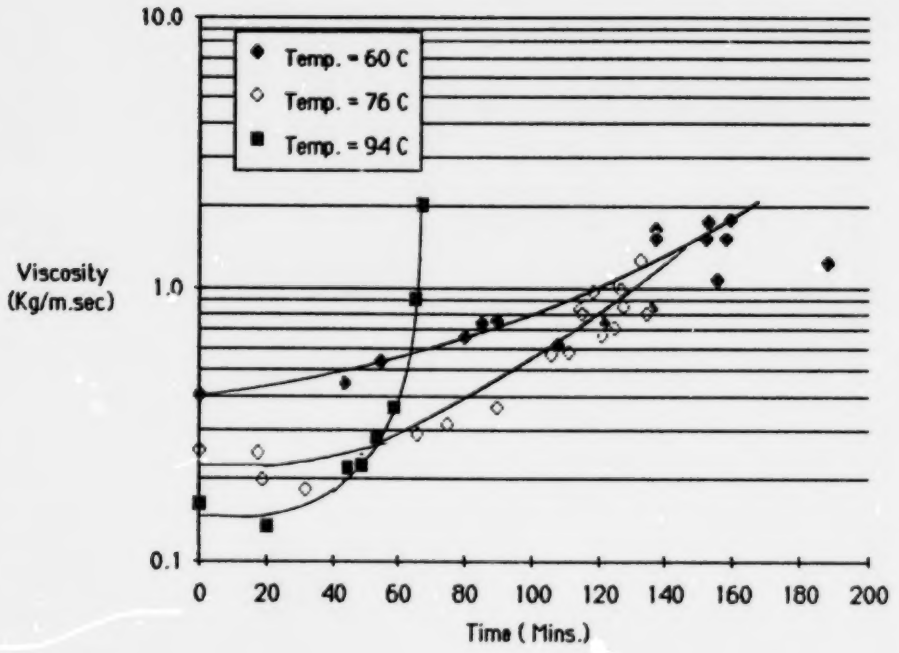


Figure 2.2: Pot-Life determination. Viscosity vs Time for various temperatures for the Ciba-Geigy epoxy mix of Figure 2.1.

the oven with the coil + mold [2]. With the relatively slow flow rates, the epoxy quickly thermalizes to the coil temperature and thus reaches low viscosity almost immediately upon entering the winding. This system is advantageous for moderate to large volumes of epoxy/hardener mix which have an unfortunate tendency to trigger prematurely if heated much above room temperature, due to the exothermic chemical reaction.

The basic procedure involved the following steps:

a) Bring the oven and coil to impregnation temperature.
b) Mix and degas the epoxy at room temperature.
c) Evacuate the coil frame and plumbing up to the epoxy reservoir exit. Bake dry.
d) Start the epoxy flow.
e) After bubble-free epoxy is observed at the exit from the coil frame , stop the flow.
f) Seal the system and complete curing the mix.

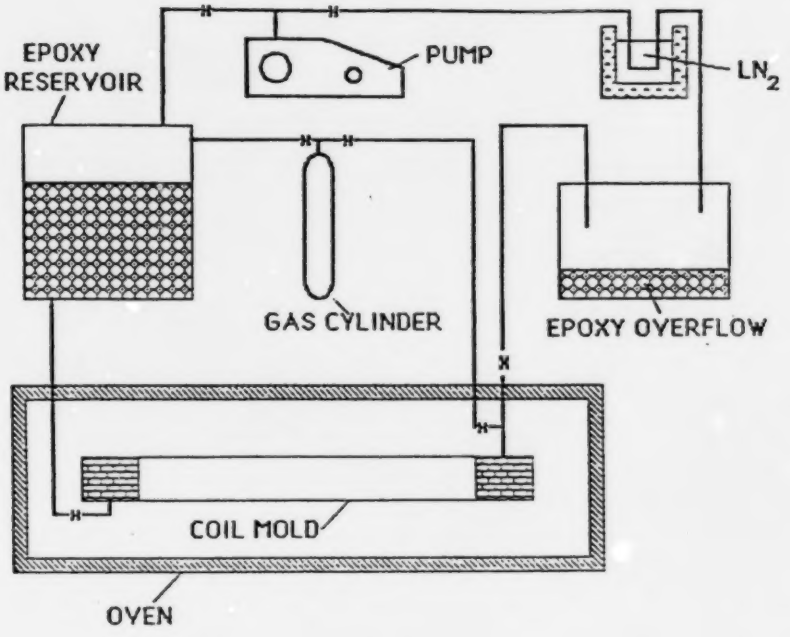


Figure 2.3: Epoxy Impregnation System

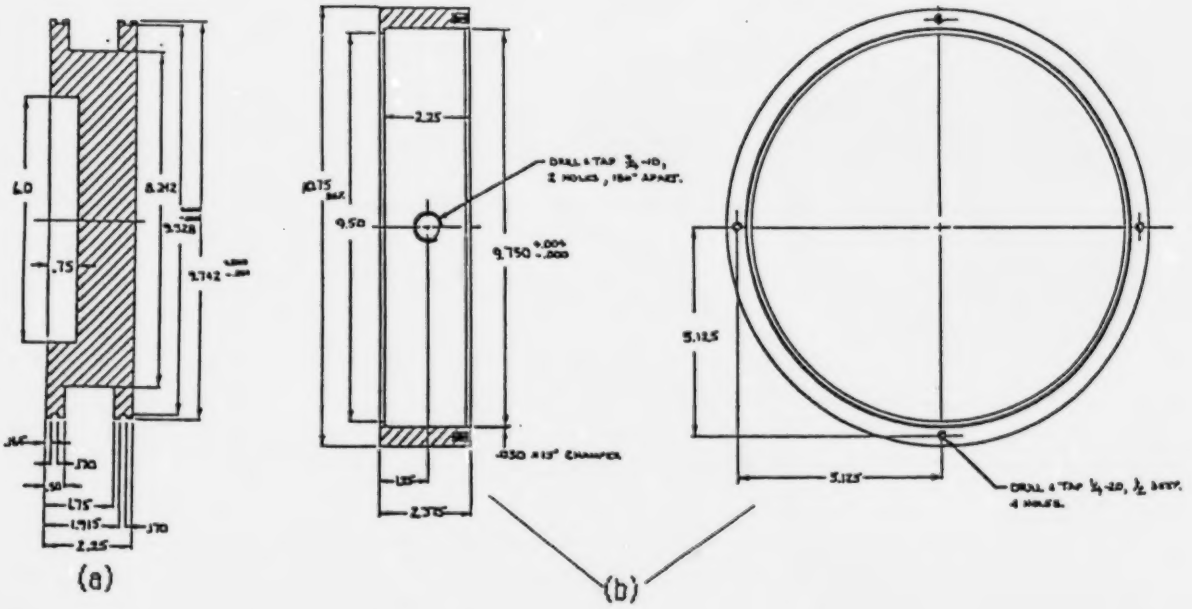


Figure 2.4: Solenoid Coil Mold a) winding ring b) sealing ring.
(Dimensions in inches)

2.3 Copper Wire Solenoids

Five copper wire solenoids have been wound, sealed, and inspected. Molds of Aluminum sealed by O-rings have been used for winding purposes (Figure 2.4). These molds were reasonably economical to fabricate and the experiments provided a good check of the coil fabrication techniques. Representative data for these coils are indicated in Table 2.1. Details of the completed mold, and the impregnated and sectioned winding are to be found in Figures 2.5 a - d.

The main goals of these experiments have been to:

a) maximize the fill factor while still ensuring complete epoxy penetration
b) minimize the void content.

The fill factors achieved were generally in the range of 70 - 80 %. The void content varied depending on the fill procedures adopted. By the fifth solenoid most of the problems had been solved and the procedures were reasonably smooth and a low void content was achieved.

The results of these tests indicated that the epoxy selected couldpenetrate wire passages within a solenoidal winding of i.d. = 20.9cm, o.d. = 24.2 cm, and sectional side = 3.4 cm . Good results were achieved with coils 3 and 5. With coil 4, a larger volume of epoxy than necessary was used in the reservoir and it triggered early, resulting in an unsatisfactory impregnation. The ambient temperature (outside the oven) was about 25C during this run. With coil 4, the wire used was reduced in diameter to obtain some information on the experimental variation in fill factor resulting from different wire sizes.

A number of the coil sections were cycled to LN_2 temperatures and then examined microscopically. Within the windings, there were no visible cracks as a result of this thermal cycling. However, on the surface next to the outer radius of the mold, cracks were evident in epoxy rich regions. It seems clear that every effort has to be taken to minimise dead volume within the mold prior to impregnation.

Table 2.1 Copper Wire Solenoid Data (Round Wire)

Coil	AWG	Layer Spacer	Pressure Curing	Fill Factor(%)	Comments
1	20	No	No	78	Voids and dry regions
2	20	Yes	Yes	70	Smaller voids
3	20	Yes	Yes	70	Low void content
4	24	Yes	Yes	70	Rapid trigger of epoxy
5	20	Yes	Yes	72	Very low void content

2.4 Copper Wire Racetracks

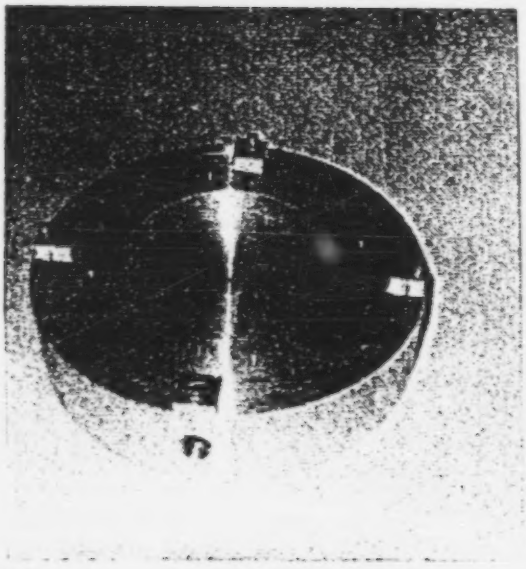
The objectives of the series of experiments with copper wire racetracks have been as follows:

1. Development of winding techniques for coils of racetrack planform.
2. Evaluation of design techniques and local welding shop capabilities for preparation of an accurate, vacuum tight mold using TIG welded SS304L.
3. Development of impregnation techniques for racetrack coils of the Canadian levitation coil size - mean length 1.06m, mean width 0.30m, section = 4 cm x 4 cm.

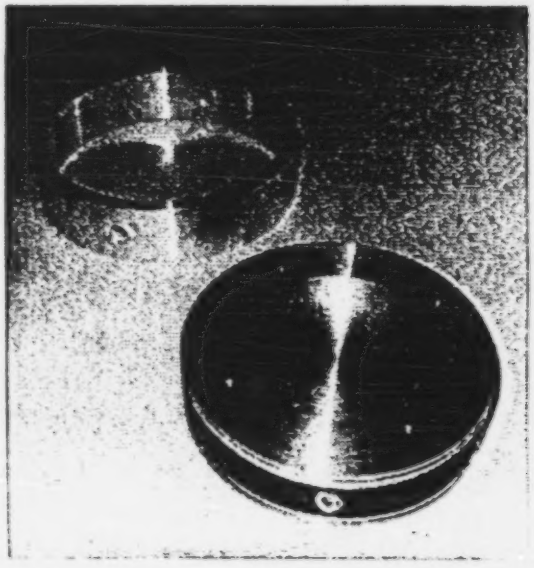
A simple, manually operated racetrack coil winder has been fabricated and tested. The wire was fed to the coil mold after passing between two rollers. The tension in the wire was adjusted by a differential-spring frictional brake mechanism acting on one of the rollers. In the present version, manual winding was adopted, and the winding could proceed at a reasonable rate. For example, a 324 turn, 4 cm x 4 cm section, full scale racetrack coil was wound in about 5 hours. The largest component of time was involved with installing the interlayer spacer material. The drive can be readily automated and this may be desirable for larger coils to improve the winding fabrication procedures. However the rate of winding will probably not be changed significantly due to the stop/start nature of the winding process.

To date, two SS304L racetrack coil frames + coils have been fabricated. The first coil frame is indicated in Figure 2.6, and consisted

Figure 2.5: Solenoidal Coil
(a) Sealed Solenoid Mold
(b) Partitioned Mold
(c) Impregnated winding
(d) View of sectioned impregnated Cu wire solenoid (AWG 20).

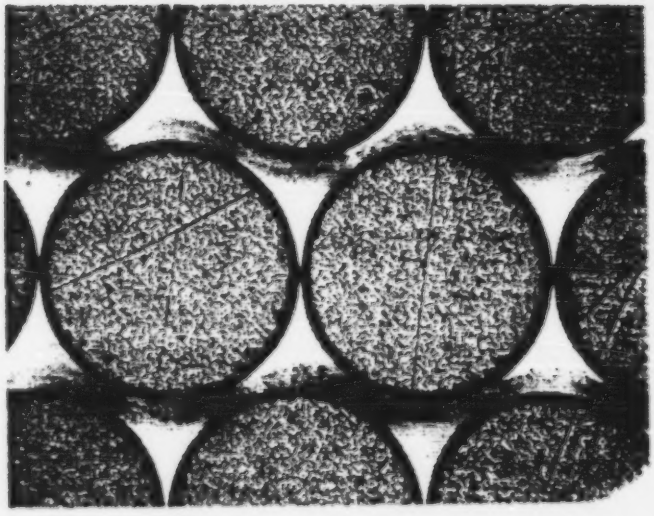


(a)



(b)

(c)



(d)

essentially of two sheets of SS304L with a strip 24 mm wide welded about 14 mm from the outer rim. This formed the base of the coil next the innermost layer. The face-plate was welded to the outer rim via extensions added to minimise heat damage to the wire. Single epoxy inlet and outlet ports were provided. The main parts of the mold were fabricated at CTF and the welding was sub-contracted. After welding, the mold frame was found to be somewhat warped and the coil section non-uniform. Nevertheless, it was decided to proceed with the impregnation in order to gain experience. Formvar insulated Copper wire (2mm x 2mm) was employed for the racetrack windings. After curing the epoxy , the face-plate was partially removed and a length of the impregnated winding extracted. Some damage was inflicted on the outer surfaces of the winding during this process.

The conclusions from fabrication and dissection of racetrack 1 were

a) a considerable improvement in the mold accuracy was required;
b) a full scale section mold should be made in order to properly determine the epoxy penetration capabilities for tight channel lengths up to 1.2m.

Accordingly, a full scale mold was prepared, in which jigging and spacers were employed to maintain accuracy of the coil section to within ±0.25mm. The main parts of the racetrack were fabricated at CTF and the welding was again sub-contracted. The completed coil frame and extracted coil section are shown in Figure 2.7. The completed coil + frame mold weighed 42.2 Kg.

The principal results from evaluation of this second racetrack were:

a) good penetration was achieved over the whole winding - no visible voids.
b) there was a very high fill factor (> 80%).
c) the impregnated composite was of high quality with greatly improved mold accuracy.

Following these encouraging results, it was decided to proceed with the mold design, fabrication and impregnation for the superconducting solenoids.

Figure 2.6: View of Racetrack Mold 1

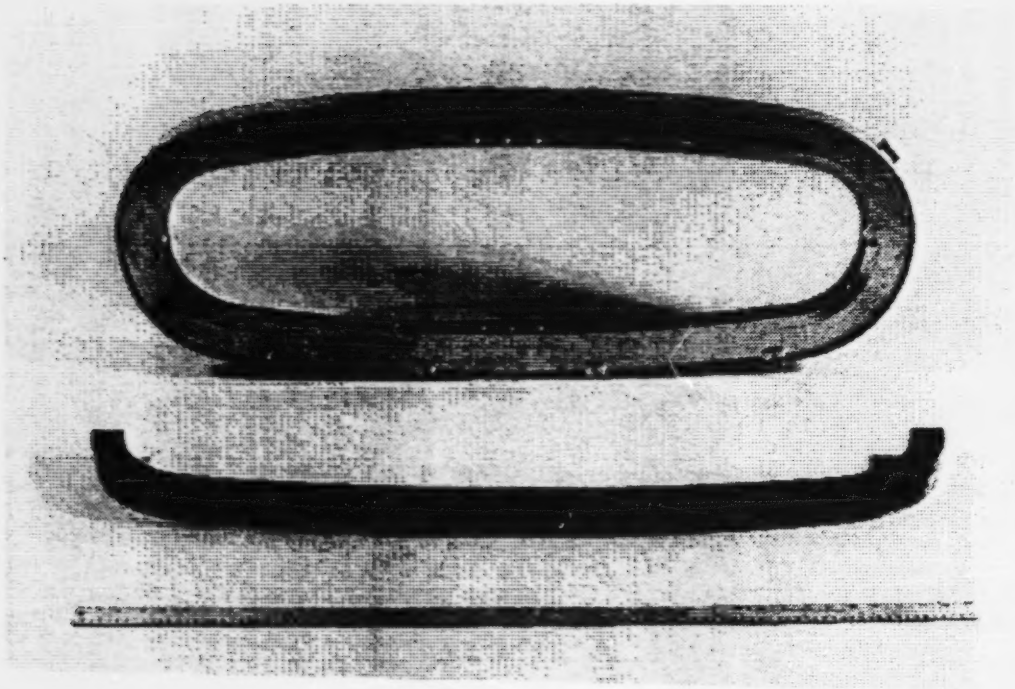


Figure 2.7: View of Racetrack Mold 2 with one half of the impregnated winding removed.

3. TEST FACILITY PREPARATION

3.1 Overall View

A facility for testing superconducting magnets has been set up at CTF Systems. Figure 3.1 gives an overall view of Bay 16 at CTF where the magnets are tested. The figure shows:

a) the 0-5V, 0- 900 Amp DC power supply
b) the test dewar, with test insert installed and the access platform
c) the coil winder fixture
d) miscellaneous LN_2, LHe_4 containers
e) the cryogen filling area.

An 800 litre LN_2 storage tank has been installed near the exit from Bay 16 to service CTF's cryogenic requirements.

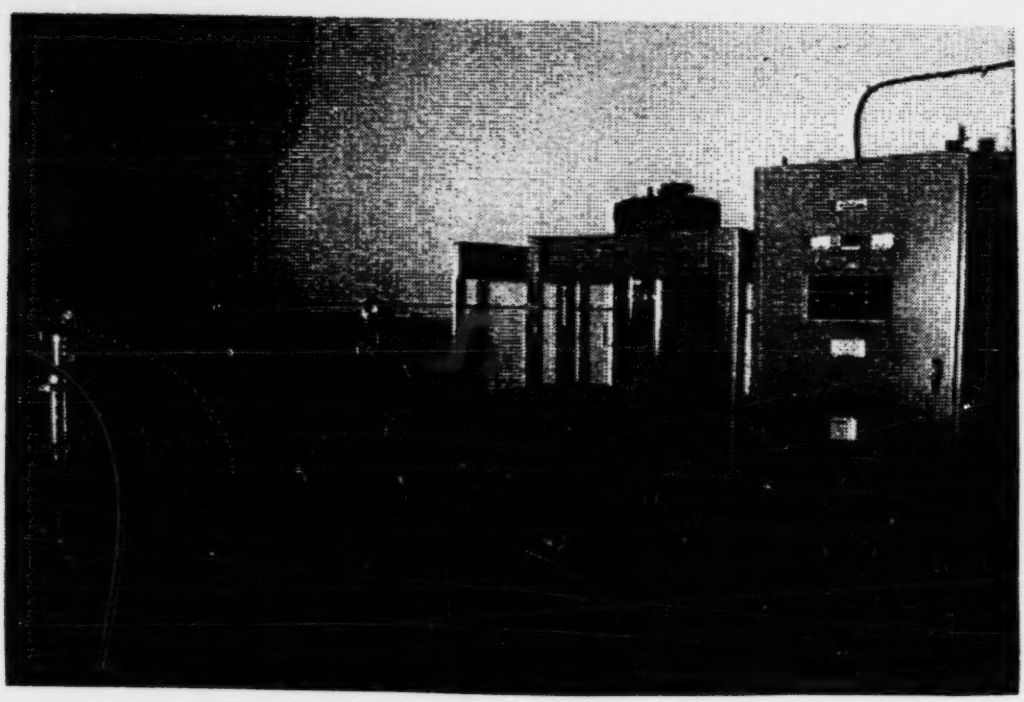


Figure 3.1: Overall view of superconducting magnet test area

3.2 Test Dewar Fabrication and Evaluation

The completed 18" access i.d. dewar is shown in Figure 3.2. The dewar has overall dimensions : outside diameter = 23", height (minus castors) = 76". This dewar has been tested both at LN_2 and LHe_4 temperatures. With the dewar and a dummy insert installed (without the current leads), the system thermalized to 0.43 litres LHe_4 /hour after 24 hours (Figure 3.3).

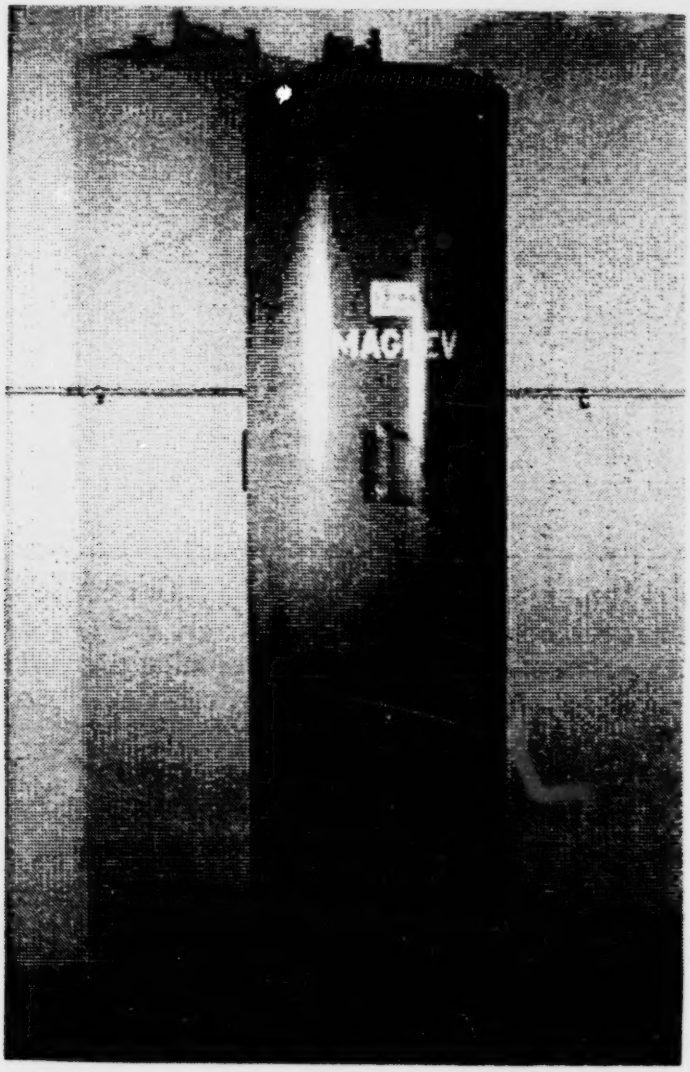


Figure 3.2: Liquid Helium Bucket Test Dewar. The dewar has neck access diameter 18 inches. The inner vacuum vessel is fabricated from cryogenic grade fibreglass, and the outer vessel walls are of Aluminum.

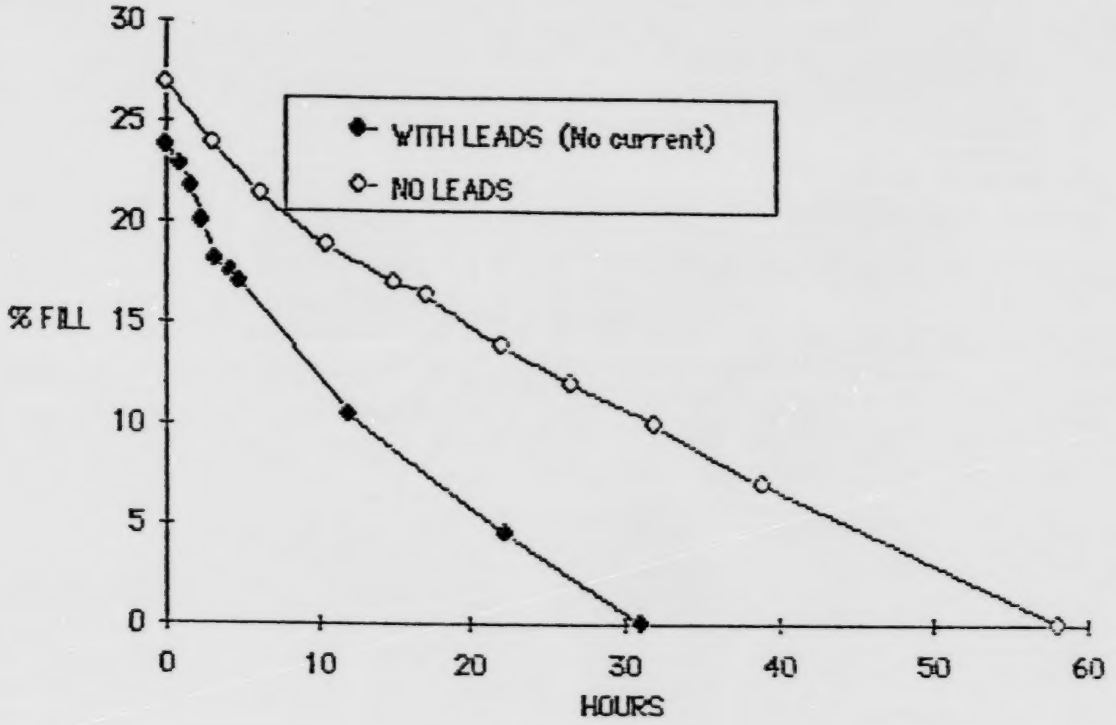


Figure 3.3 LHe_4 Boil-off Rate Test Data measured with a superconducting wire level indicator. The NO LEADS data were collected with a low loss baffle in the dewar neck consisting of styrofoam plus a number of spaced radiation shields. The WITH LEADS data were collected using the test insert of Figure 3.4, but without any current flowing in the leads. The calibration for the liquid helium level indicator was 1%=1Litre. The dynamic boil-off rate could also be estimated using a flow meter which was separately calibrated for Helium gas.

3.3 Test Insert Fabrication and Evaluation

An insert suitable for testing solenoids up to 18" outside diameter (45 cm) has been completed and tested (Figure 3.4). Its inner length has been extended to allow testing of racetrack coils of the Canadian levitation magnet design (major axis vertical). The vapor cooled current leads for the superconducting coil are designed for a current capacity of 900 Amps. A view of the top plate of the insert is given in Figure 3.5. The completed system has been cooled to liquid Helium temperatures, yielding a thermalized LHe_4 boil-off rate of about 2 litres/hr without energising the current leads. With the leads energised to 900 Amps, a boil-off rate of about 3 litres/hour was observed.

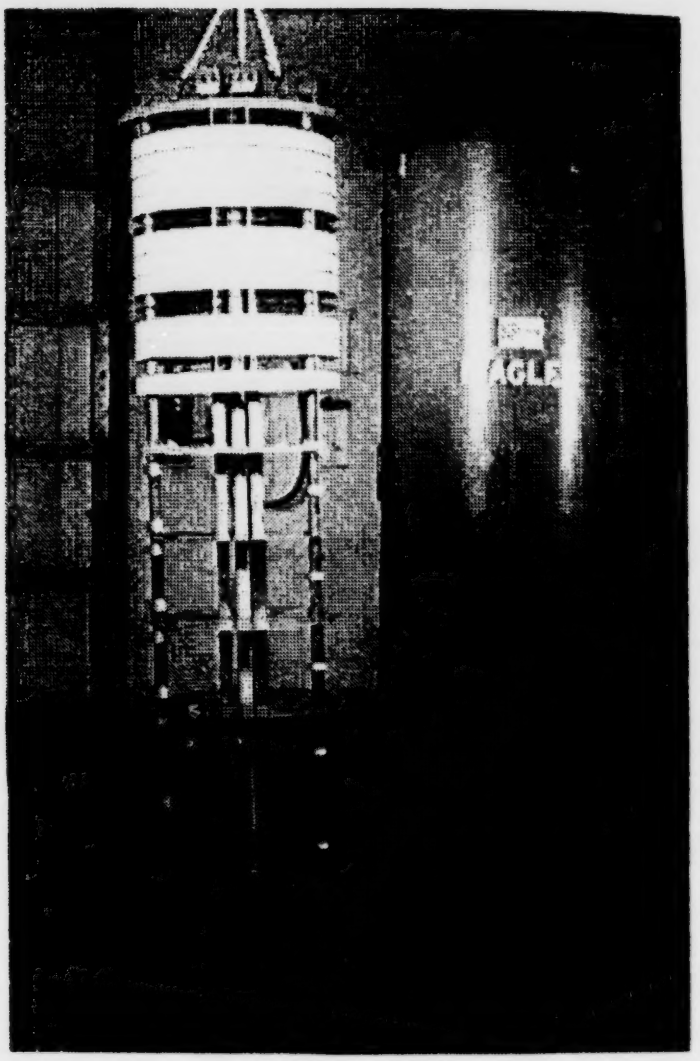


Figure 3.4: View of Test Insert

3.4 DC Power Supply Installation

For general purpose testing of superconducting magnets and components CTF has acquired a DC power supply (0-5V, 0-900 Amp) with output current stability better than 0.01% (Figure 3.1). The unit was fabricated by Philtek Electronics of Richmond, B.C., and met or exceeded all specifications when tested with a water cooled resistive load at CTF. All standard interlocks have been included, as well as an interlock for a quench detection circuit connected to the coil.

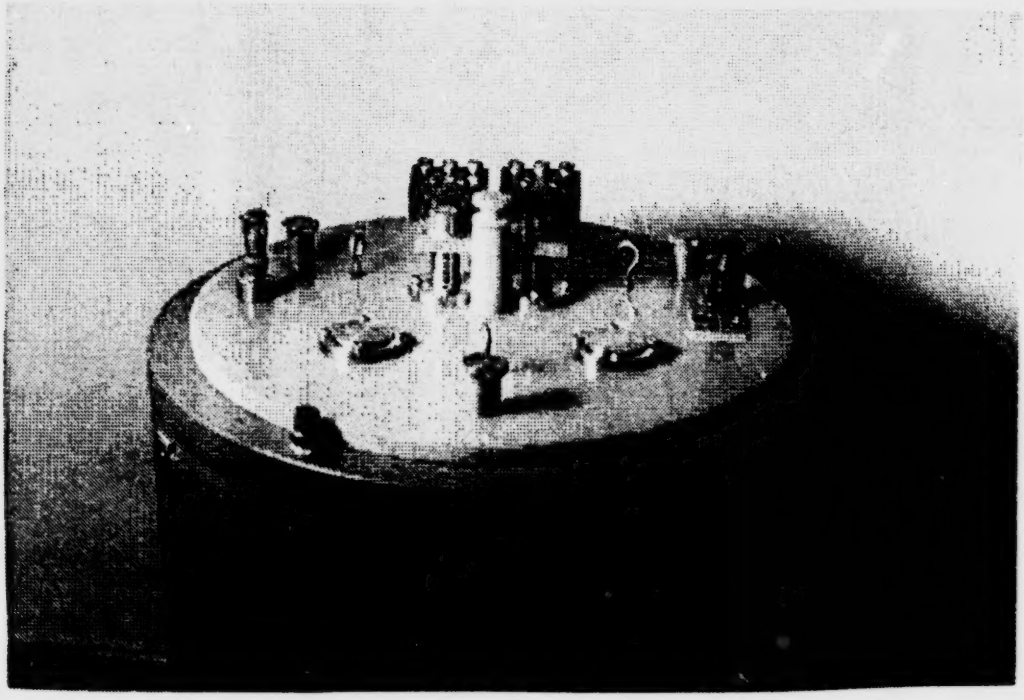


Figure 3.5: View of the Top plate of the Test Insert

4. SUPERCONDUCTING SOLENOID FABRICATION

4.1 Coil Frame Design and Fabrication

After completion of the racetrack coil 2 (Figure 2.7), the design of the superconducting solenoid mold was reviewed. After some analysis, it was decided to build the mold indicated in Figure 4.1. The mold was of SS304L sheet, thickness 2mm, and was welded from parts fabricated at CTF. This mold was intended to allow the coil to be tested fully immersed (4-sided cooling), and also with 2-sided cooling at some later date . The 2-sided cooling design follows the ideas generated for the racetrack coil mold for the final levitation magnet design (Appendix A).

4.2 Coil Winding and Impregnation

Prior to winding and impregnating the first superconducting solenoid, some experiments were conducted to ensure that a high fill factor could be achieved (e.g. > 80%). These investigations basically involved optimizing the winding techniques for model solenoids using square copper wire. A brick wall type winding method was developed in an attempt to increase the impregnated coil interlaminar shear strength (Figure 4.2).

In addition, some experiments were conducted to determine the best method for sealing the inlet and outlet wires for the coil. The final sealing method involved wrapping the superconducting wire with thin fibreglass cloth, and then sealing the wire exit tube holes with a filled epoxy whose thermal contraction between room and liquid helium temperatures approximately matched that of the SS304L.

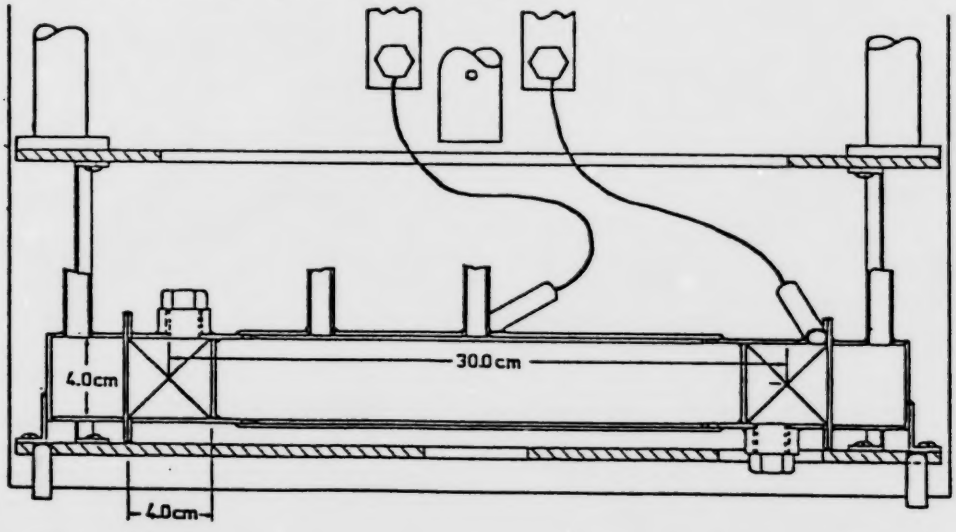


Figure 4.1: Section drawing of mold for superconducting solenoid

The coil was wound and sealed following the procedures developed for the model copper wire coils. Parameters for the superconducting wire are indicated in Table 4.1 with a sectional view in Figure 4.3.

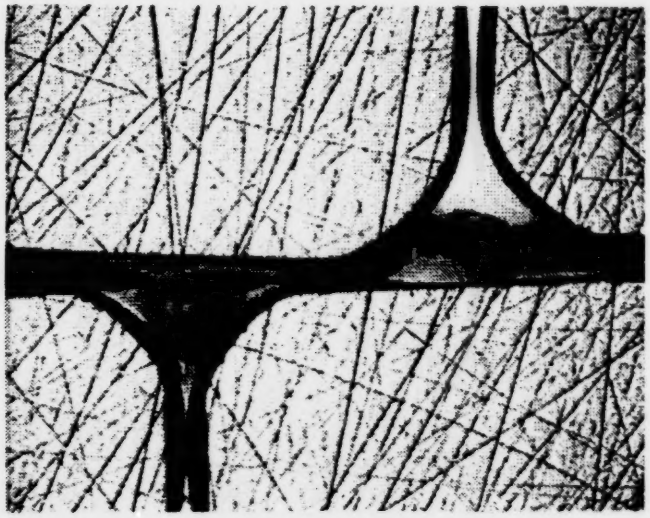


Figure 4.2: "Brick-type" winding pattern for square copper wire, where each wire layer is displaced laterally by one half the wire width. The fibreglass interlayer spacer is clearly visible.

Table 4.1 Superconducting Wire Parameters (Supplier : Oxford Airco)

Superconducting Alloy	Nb 46.5 wt. % Ti
Size	1mm x 2mm nominal (bare) (Accuracy ± 0.002 inches)
Cu/Sc ratio	2:1
Number of Filaments	426
Corner Radius (inch)	0.013-0.015 inch
Insulation	Heavy Formvar
Critical Current (Guaranteed) (4.2K and 4 Tesla magnetic field parallel to the broad face)	1480 A
RRR of Cu	> 150:1
Twist pitch	1 turn/ 1.5 inch

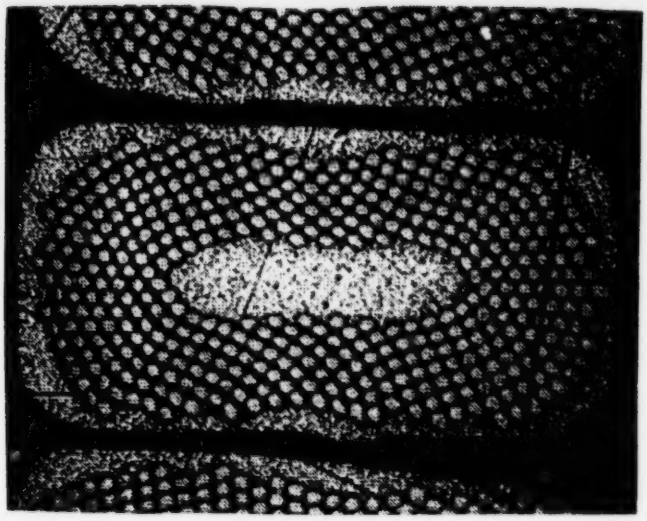


Figure 4.3: Sectional view of 2:1 Cu:NbTi wire.

4.3 Coil Completion

A view of the completed solenoid plus frame is indicated in Figure 4.4. The wires were successfully sealed at the coil entry and exit tubes, and mounting points for the 900 A bus bar leads were attached. These bus bars are of commercial design consisting of high critical temperature Nb_3Sn tape superconductor soldered between shunting copper bus bars. Provided one end of the bus bar is in liquid helium, the Nb_3Sn remains superconducting. The joints between the bus bars and the coil wires were designed following the principles outlined by Wilson [3].

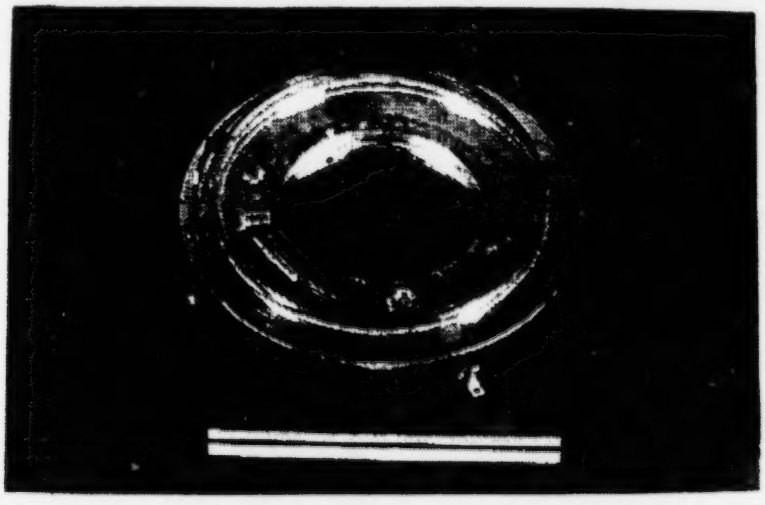


Figure 4.4: View of completed solenoid sealed in its mold.

5. SUPERCONDUCTING SOLENOID TESTING

5.1 Quench Characteristics

The coil was clamped to the test insert (Figure 5.1) and the current and instrumentation leads attached. Cooldown tests were performed in LHe_4 in order to characterize the performance of the coil as a function of charging current. Figures 5.2 and 5.3 present the measured data for the test solenoid. The tests basically consisted of fully immersing the coil in LHe_4 and then increasing the current until the coil quenched. Almost all the coil energy was dissipated in the LHe_4. The quantity of LHe_4 which was boiled away during each quench was recorded and the tests repeated at 1 hour intervals for a given LHe_4 fill. A summary of the coil parameters and some of the results are presented in Table 5.1.

In Figure 5.2, the quench currents are plotted against the trial number for 11 trials overall. The first 5 trials were conducted without warming the coil above 4.2 K. Trials 6, 7 and 8 were conducted after the dewar had been warmed to liquid nitrogen for 4 days and then re-cooled to 4.2 K. Trials 9, 10, and 11 were conducted about 2 weeks later after the coil had been fully warmed to room temperature and then re-cooled to 4.2 K.

During each test, the magnetic field was monitored at various points in the vicinity of the dewar using a Hall probe. This Hall probe had been calibrated to about 1% accuracy, using an electromagnet at Simon Fraser University Magnet Laboratory. The magnetic fields at the test points were also computed by numerically integrating the Biot formula for the present solenoidal dimensions. These computations were also cross-checked using tabulated magnetic field values for solenoidal coils [4]. The measured and estimated fields due to the superconducting solenoid agreed to within 2%.

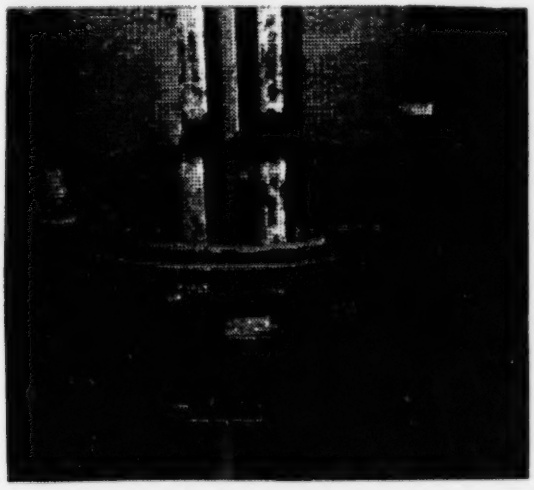


Figure 5.1: Section of test insert base region and superconducting coil

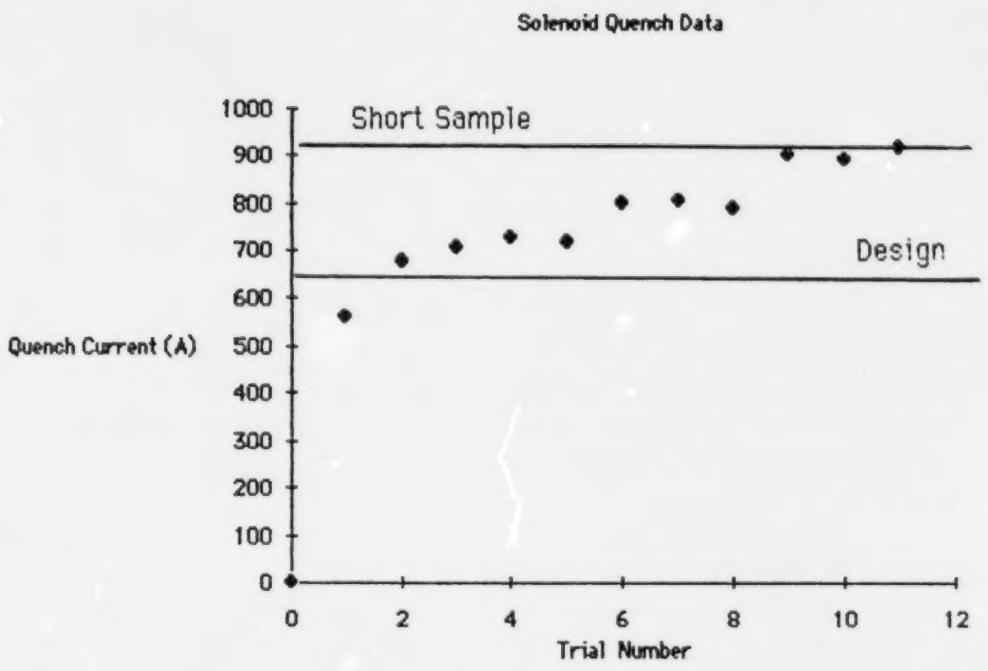


Figure 5.2: Coil current versus trial number for the test superconducting solenoid quench (mean diameter =30 cm, section = 3.8cm x 4 cm).
Runs 6, 7, 8, - coil warmed to LN_2 then recooled to LHe_4.
Runs 9, 10, 11, - coil warmed to 300K then re-cooled to LHe_4.

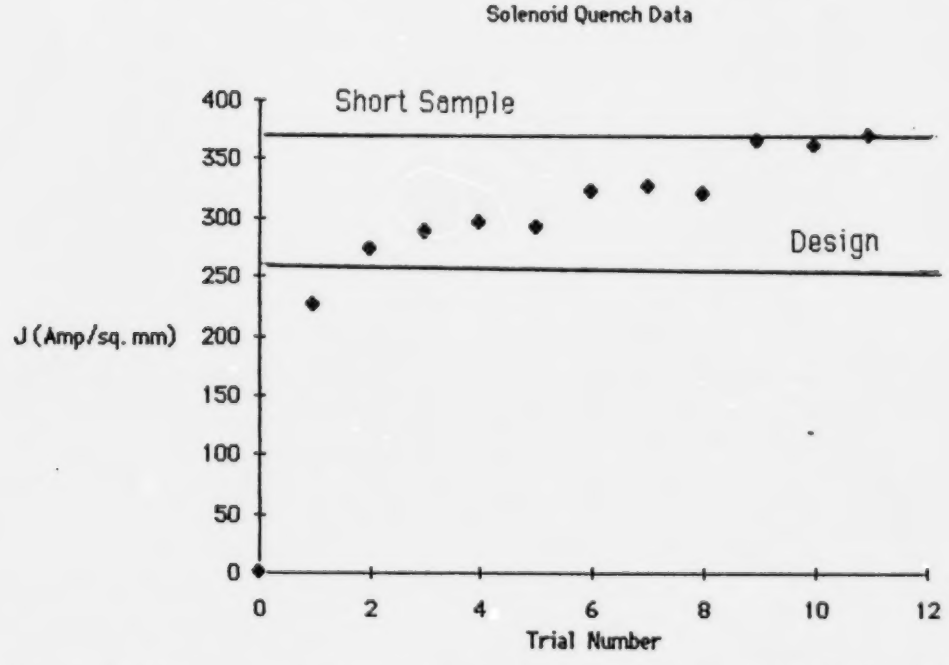


Figure 5.3: Overall coil quench current density for the data of Figure 5.2.

Table 5.1 Coil Parameters and Major Results

I.D. (cm)		26.0
O.D. (cm)		33.6
Length (cm)		4.0
No. of turns		604
Estimated fill factor		0.82
Estimated self inductance (H)		0.157
Measured self inductance (H)		0.16
Design overall current density (A/mm^2)		263.15
Design current (A)		662.25
Measured peak quench current (A)		914 ± 2
Stored energy at design current	(KJ)	35.09
Stored energy at peak quench current	(KJ)	66.83
Design magnet strength	(KAT)	400
Peak magnet strength at 914 A	(KAT)	552

The data indicate that the coil reached the design current after the first quench. Following 7 more quenches, the coil trained up to the short sample critical current. In fact, the last 3 points are all within 1-2 % of the short sample value which was interpolated from data points for the Oxford Airco 2:1 Cu:NbTi wire. The peak quench current measured with the present coil was 914 ± 2 A (trial #11). Note that the short sample critical current (I_c) measured by Oxford Airco was 1700 A at 4 Tesla, 4.2 K, some 15% higher than the guaranteed value of 1480 A (Table 4.1). At 7 Tesla and 4.2K, their measured critical current (I_c) was 900 A. Both these values were measured to 1% accuracy.

An equivalent plot was also made of the overall coil current density as a function of number of trials (Figure 5.3). The accuracy of these data points is probably no better than ± 3 %, since one has to estimate the coil sectional area. Note that the quench current density in the NbTi filaments corresponding to the current of 914 Amp was 1370 A/mm^2, at an estimated field of 6.4 Tesla.

The volume of LHe_4 boiled off during a quench provided a further indirect check of the coil performance. The inductive energy ($1/2LI^2$) dumped into the liquid helium for each quench current (I) was computed for the coil (L = 0.16H), and was found to agree with the latent heat of vaporization for the quenched helium to within 3%.

5.2 Current Ramping Experiments

During the initial quench tests (trials 1-5), the current in the coil was ramped manually. In all later tests, the current was ramped electronically at selectable rates. Generally for trials 3 through 11, the final quench point was approached slowly with the current ramped at 0.3-0.5 A/second. During the trials 10 and 11, attempts were made to quench the coil using higher current ramp rates up to 7 A/sec, which was the upper limit available with the electronic sweep. The initiation current was set at 700 A and the current then ramped to 800 amps at various rates. No quench could be induced for rates up to about 7 A/sec. This was repeated over the range 800 A to 910 A with the same result.

The peak field slew rate was estimated to be 0.049 T/sec for the 7A/sec current rate. This is a factor of 14 smaller than the 0.7 T/sec field slew rate estimated to be generated in the levitation coils by the Maglev vehicle dynamics (0.3% of B_{max} at 7.5Hz). This latter slew rate implied a current ramp rate requirement of 100 A/sec and a minimum compliance voltage for the power supply of $Ldi/dt = 0.16 \times 100 = 16$ volt, which is above the maximum output of the present supply. In order to fully test the coil, current ramp rate tests should be carried out at rates up to 100 A/sec at some later date.

6. ANALYSES OF DATA

6.1 Quench Analysis

The software code "Quench" [3,5] has been employed to predict the behaviour of the constructed solenoid after a quench was initiated. The coil and power supply circuit are outlined in Figure 6.1, where a shorting resistor of 50 milliohm was connected across the current leads at room temperature. Figures 6.2 and 6.3 present the peak post-quench temperature and internal voltage induced in the coil as a function of the coil current from 400 A up to the maximum of the experiment (914 A). In all cases, $\geq$ 90% of the total coil energy ($1/2LI^2$) was dissipated in the coil after the quench.

For currents close to the short sample critical value, the peak temperature was 110 K, and the peak voltage was 970 V. These predictions indicate that epoxy impregnated coils constructed with the present technology can withstand repeated quenching where most of the coil energy is dissipated internally.

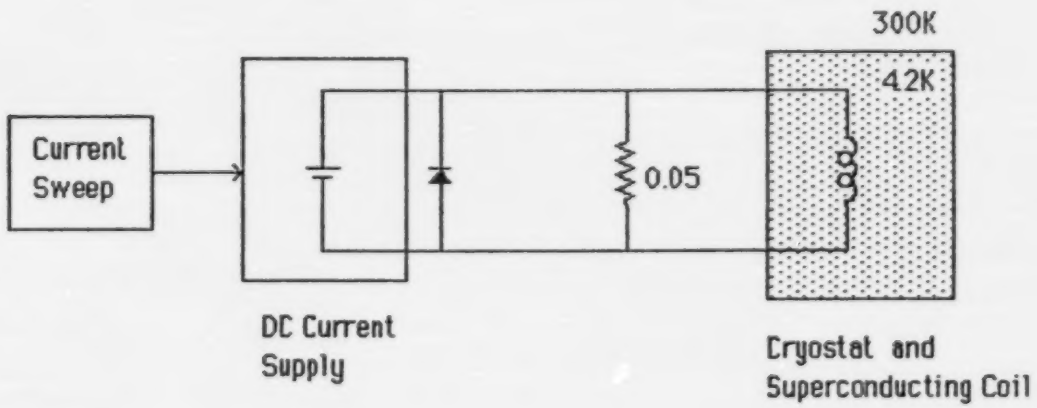


Figure 6.1 Coil and power supply test circuit

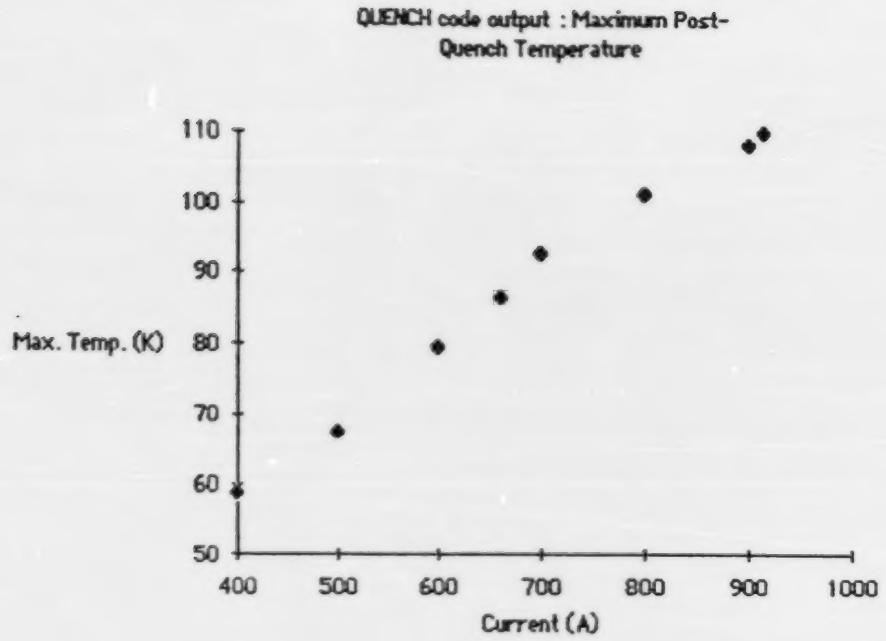


Figure 6.2: Peak temperature estimate as a function of current from the QUENCH code for the test superconducting solenoid in the circuit of Figure 6.1.

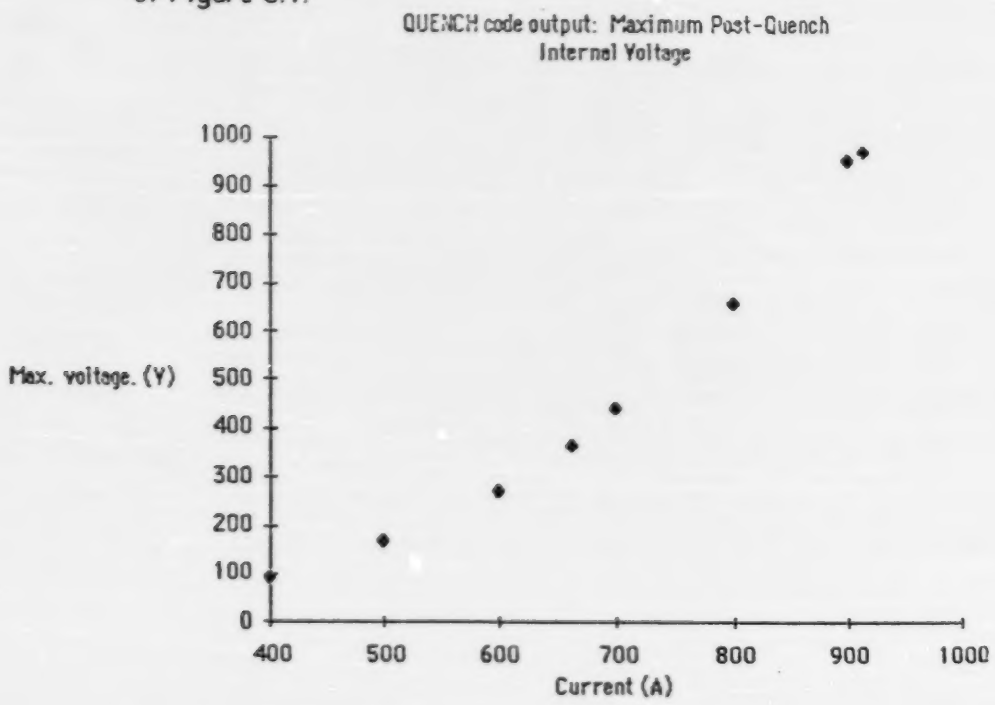


Figure 6.3: Peak internal voltage estimate as a function of current from the QUENCH code for the test superconducting solenoid.

6.2 Stress Analysis

The coil and SS304L frame have functioned reasonably well and there was some interest in modelling the peak stress resulting in the coil composite from the combination of winding tension, impregnation, cooldown to LHe_4 temperatures and energising (Lorentz load). The 2-dimensional model of Arp [6] was adapted for the present case. In Figure 6.4, the total circumferential stress at the coil inner radius on the median line is plotted against the coil current for currents up to 914 A. The total circumferential stress St is given by

$$St = Sw + Sc + Sf + SL$$

where Sw = circumferential winding stress due to a uniform 8Kg tension
Sc = circumferential composite thermal contraction stress
Sf = circumferential differential thermal contraction stress between the SS304L frame and the impregnated composite
SL = circumferential Lorentz stress due to energising the coil.

The curve for the estimates is due to the fact that the Lorentz stress is proportional to the square of the coil current and is added to the (constant) terms Sw, Sc and Sf. For epoxy impregnated coils with sizing and geometry similar to the present case, Arp has estimated that his analytical formulation agreed with 3-dimensional finite element computations for solenoids to within 20% [6]. Accordingly, the 173 MPa peak hoop stress computation for the present impregnated solenoid (at 914 A bias current) is viewed as a reasonable estimate.

In tension, the fracture toughness of epoxy resin at 4.2 K is in the range of 145 - 200 MPa [8], and thus a possible source of the few training cycles with the present coil was brittle fracture of the epoxy matrix as the current was increased. A range of complex behaviour related to mechanical disturbances in epoxy impregnated coils has been recently reported by the MIT group in a series of papers [7, 8, 9,10].

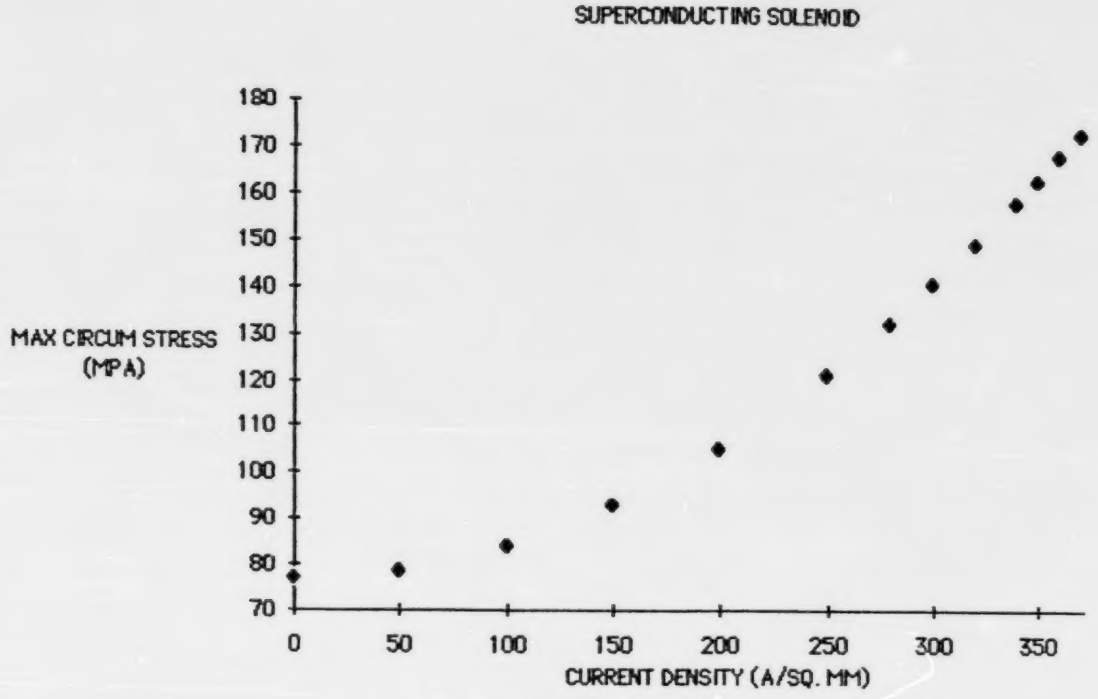


Figure 6.4: Estimated maximum circumferential (hoop) stress as a function of coil current for the test solenoid with i.d. = 13 cm, o.d. = 16.8 cm, and section = 3.8 cm x 4 cm [6].

7. CONFERENCES

During the period of the contract, there were two conferences on Maglev related topics:

1. Maglev Transport '85, Tokyo, September, 1985.
2. Maglev and Linear Drives, Vancouver, May, 1986.

During May, June and July of 1985, an overview paper describing the Canadian EDS Maglev program was prepared for the Tokyo conference which was held at the Keidanren Kaikan, Tokyo, September 16-20, 1985. The paper was entitled "An Overview of Canadian Maglev Research and Development" co-authored by N. Rudback, W. F. Hayes , A. R Eastham, A. A. Fife and M. Audette. The paper was presented at the conference by A. A. Fife.

During the trip to Japan, site visits were made to

a) Hitachi Mito works - Linear motor developments for transit.
b) JAL HSST at Expo-85, Tsukuba
c) JNR EDS Maglev vehicle at Miyazaki
d) Toshiba R&D Centre, Kawasaki (Dr. Ogiwara)
e) Energy Conversion Technology Inc. (ECTI), Kamakura, (Dr. Ishizaki).

The conference and site visits proved useful in outlining the current status and plans for both the EMS and EDS technologies. In addition, information was gathered on the current status and future directions of the development and applications of superconducting magnets and cryocoolers.

The visit to the Toshiba R. & D. Centre (accompanied by Mr. P. L. Eggleton, Science Counsellor for the Canadian Embassy) resulted in frank and informative discussions on various topics concerning EDS Maglev. The Toshiba EDS Maglev group expressed interest in the present activities and future plans for the Canadian Maglev R & D. Dr. Ogiwara was also interested in the racetrack coil frame designs, which were presented as part of the Canadian overview paper. (Some sketches were sent to him at a later date). A trip report has been prepared by CTF Systems describing the activities in Japan during this trip [11].

8. PLANNING AND SPIN-OFF BENEFITS

8.1 Near-Term Spin-off Benefits from EDS Maglev R & D

Two reports have been prepared as part of this contract in order to examine near-term spin-off benefits flowing from EDS Maglev developments in magnet and cryocooler technologies [12,13].

Figure 8.1 presents a summary of the applications of superconductors to (a) superconducting magnets (b) superconducting electronics and also provides approximate ranges of refrigeration power requirements in the temperature interval 4.2-4.5 K.

The report on superconducting magnets identifies at least three applications areas where potential spin-off benefits exist:

(1) research magnets
(2) magnetic separation
(3) limb imaging via nuclear magnetic resonance (MRI)

Research magnets appear to be an on-going requirement of moderate activity. A typical example is a thin solenoid system for the TRIUMF accelerator beam lines.

Magnetic separation using superconducting magnets is attracting interest due to (a) improved separation efficiency and (b) greatly reduced ongoing power requirements when compared with conventional (HGMS) magnetic separation methods. Eriez, a company in Erie, Pennsylvania, is currently supplying a $2.5 million superconducting separator for the Huber Clay Corporation of Macon, Georgia. This unit is expected to provide power savings of 85% with extra capital costs of no more than 25%. (Note that conventional HGMS units can weigh up to 250 tons and consume 0.5 megawatt of electricity costing $60-70/hour in power alone). Developments are also taking place in the U.K. at IRD, and Cryogenic Consultants Inc. The most imaginative solution for continuous throughput is the drum separator being developed in West Germany.

Magnetic Resonance Imaging (MRI) received a boost in early 1985 when General Electric of the USA obtained permission to supply whole body systems for routine clinical use . Several hundred MRI shipments are expected by the end of 1986. An alternative to the whole body units are reduced scale systems which could be used for imaging e.g. the human head alone, or limbs. In addition, smaller scale systems are of great interest for

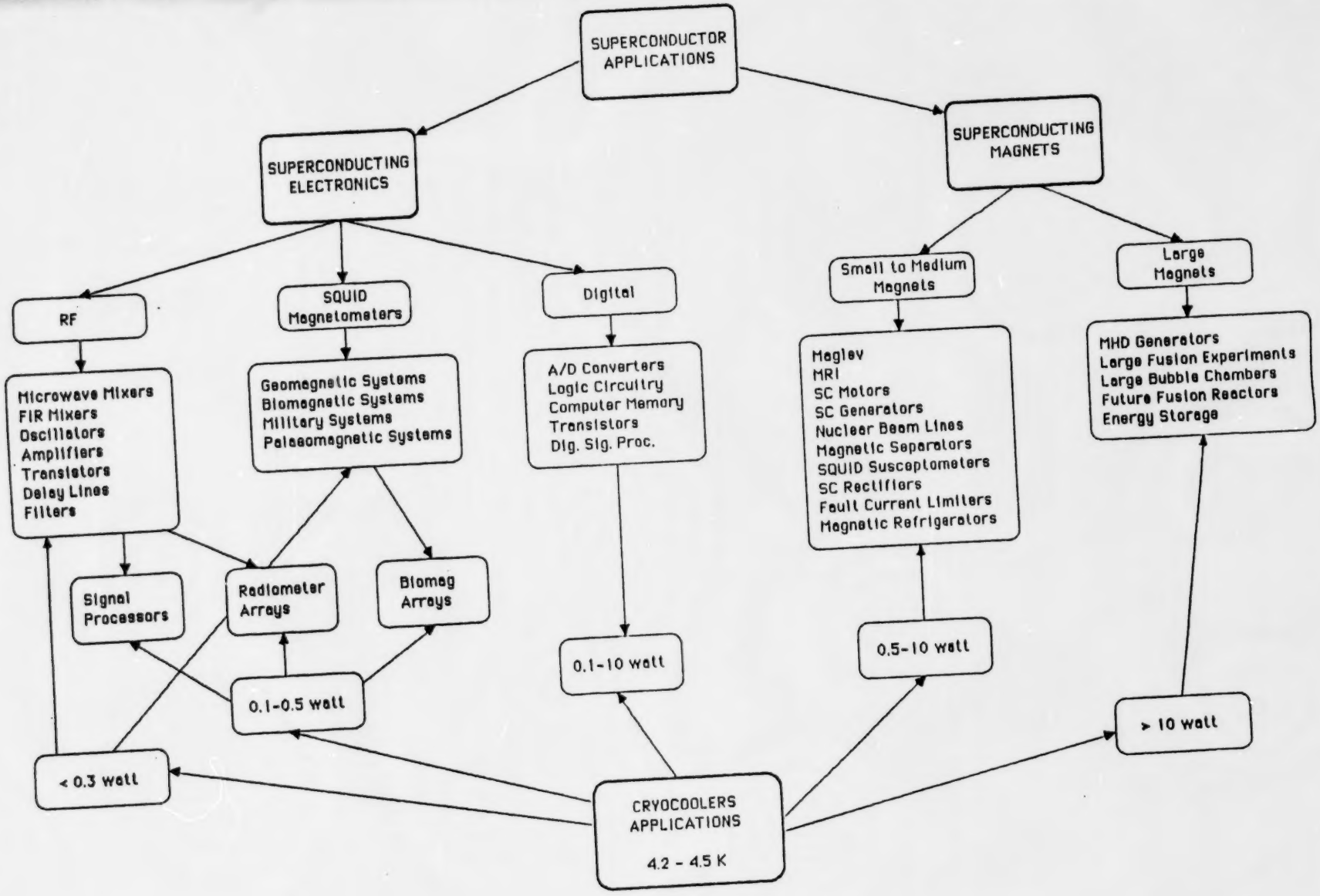


Figure 8.1: Outline of applications of superconductors and cryocoolers to superconducting magnets and superconducting micro-electronics. Approximate ranges of refrigeration are given for the temperature interval 4.2 - 4.5 K.

biological research using relatively small animals. Since there are many medical research laboratories world wide, there is considerable market potential.

Superconducting electronics is expanding rapidly and the technical edge offered by superconductive circuits is leading to many new opportunities in research , commercial, industrial and military fields. Table 8.1 outlines some of the applications of these circuits to low frequency magnetometry, RF, microwave devices and circuitry and digital processing.

Superconducting electronics , specifically low frequency magnetometry forms a vital element of CTF's activities. CTF is one of a handful of companies world-wide developing and marketing SQUID-based magnetometers, and from the current sales projections can forecast excellent prospects especially in the field of clinical biomagnetism.

CTF is presently extending its technological base to the field of planar Josephson Junction micro-electronics, in order to secure and also advance its technical and market position, both in SQUID based systems and also to the other opportunities outlined in Table 8.1.

Recently the company has made a substantial investment in a custom thin film sputtering facility. This facility has been designed for the preparation of a range of superconducting materials, structures and devices, fabricated using state of the art lithographic techniques. Of particular interest for electronic applications are the refractory high critical temperature (T_c), high critical field superconductors such as NbN, Nb_3Sn, Nb_3Ge etc, which have T_c's in the 10 to 23 K temperature range. Interestingly, several research groups (e.g. Toshiba) are investigating the possibility of fabricating materials such as NbN in thin film form on and geometry suitable for magnet applications. (These new structures may provide alternatives for the present strain sensitive technology for the high T_c alloys).

The subject of cryocoolers is strongly connected with the eventual viability of <u>all</u> superconducting systems. In fact, the lack of suitable cryocoolers is a serious impediment to more widespread superconductor applications. The ideal cryocooler for superconductors would have the following properties :

- reliability similar to the household refrigerator
- stable, operating temperature selectable over the range 1 K - 20 K

- flexible design so that refrigeration output can be varied from a few mW to ≈10 Watts
- high efficiency in the temperature range 1 K - 20 K
- possibility of low volume, lightweight design
- trouble-free operation in fields of several Tesla
- essentially zero vibrational input
- essentially zero magnetic signature
- reasonable cost

Needless to say this wonder machine does not exist. Reference 13 outlines various cryocooling methods and discusses some recent developments of concepts, hardware systems, and materials technologies which are expected to improve the performance of the current generatioon of cryocoolers. Tables 8.2 and 8.3 present some specifications for various superconductive system applications, both in the area of magnets and electronics.

The most popular cryocooler at the present time uses the Gifford-McMahon cycle. Tens of thousands of these systems have been installed in cryopumps for the semiconductor wafer fabrication industry and other high vacuum environments requiring a non-contaminating pump system. They generally have base temperatures of the order of 10K and excellent reliability (normally > 2×10^4 hours MTBF), but low efficiency.

Some of the more recent advances and goals in cryocooler technology include:

- development of high heat capacity regenerative heat exchangers using rare earth materials such as GdErRh. This has enabled regenerative machines operating on the Stirling cycle to reach LHe temperatures (previously impossible)

- development of thermally driven $LaNi_5$ hydride compressors for cascaded J-T cooling to ≈20K

- development of cascaded J-T systems operable from 300K to 4K

- development of Carnot cycle magnetic refrigerators of efficiency > 50%, operating between 20 K and ≈4 K

- development of miniature expansion turbines with gas bearings for refrigeration capacities down to 10 W at 4 K

- development of plastic (non-magnetic) Stirling machines with base temperatures ≈ 6 K

- development of ultra-low wear systems which incorporate linear motor drives, magnetic and gas bearings, and gas springs (deep space missions of 3-5 year duration).

The research and development field of cryocoolers is rather active and breakthroughs have occurred which are expected to improve the acceptability of superconductive systems in the next 3-5 years.

CTF Systems is vitally interested in cryocooler technology since, in the relatively near future, it is expected that all superconductive systems will have to be cryocooled (from the points of view of convenience and cost, and recognizing the dwindling He_4 gas resource).

Table 8.1 : Outline of Superconducting Micro-Electronic Applications

Interest	Device	Sensitivities	Specific Applications
Low Frequency Magnetometry	SQUID Magnetometers Gradiometers	Bmin : $\approx 5 \times 10^{-15}$ T rms/$\sqrt{Hz}$	Biomagnetism Geomagnetism Airborne Surveying Military
RF (.01-1 GHz)	SQUID Amplifiers	$T_N \sim 1°K$ 20 db at 400 MHz	Ultrasensitive NMR
Microwave (1-300 GHz)	Parametric Amps SIS Mixers Radiometric Arrays Receivers Oscillators Filters Multiplexers	$T_N \sim 6K$ at 8 GHz 10 db gain Quantum limit possible	Communication Spectrocopy, Reder Fast Imaging Satellite Navigation
Signal Processing	Convolver Tapped Delay Line SC Strip Line SIS Mixer		Pulse Compression Radar Spread Spectrum Communication Electronic Warfare
FIR (300-2000 GHz)	SIS Mixers Radiometric Arrays	Quantum Limit possible	Astronomy Fast Imaging
Digital	J.J. SQUID 3 Terminal Devices	10^{-18} switching energy	A/D Conversion Memory Logic

Table 8.2 Cryocoolers for superconducting magnets : qualitative comparison of specifications.

Application	Refr. Power (W)	Operating Temp (K)	Temperature Stability (K)	Efficiency	Min. Service Period (h)	MTBF (h)	Temp. Env (°C)	Acceleration Env. (g)	Vib. Freq. Hz (environment)	Magnetic Env.	Size (m)	Weight (kg)
MAGLEV	1-5	4-5	±0.1	Max	5000	>10,000	(-50-+40)	±10	~0-10	High	0.30x0.8 L	≤ 40
Magnetic Refr. (Maglev)	1-5	4-5	±0.1	Max	5000	>10,000	(-50-+40)	±10	~0-10	High	0.30x0.8 L	≤ 40
MRI	0.5-2	4-5	±0.05	Medium	5000	>10,000	0-30	< 1	(Hospital)	Low-Medium	No Problem	No Problem
SC Motor	1-5•	4.2	±.1	Max	5000	8000	0-40	±2	(Ship)	High	.22x1.40L(II)	450
SC Separator	0.5-5	4-5	±0.1	Medium	5000	>10,000	0-40	<0.5	(Mine)	High	No Problem	No Problem
Nuclear Beam Lines	≤1/magnet	4-5	±0.1	Medium	5000	10,000	0-30	<.1	(Radiation)	High	No Problem	No Problem
SQUID Suscept	≤0.5	4-5	±.005	Medium	5000	10,000	0-30	<.1	(Lab.)	Medium	No Problem	No Problem

• (I) The ~ 20,000 HP homopolar motor prototype magnet described by Appleton (IRD) had a LHe cooling rate of ~18L / hr.
(II) The 3000 HP motor described by Marshall (GE) had a LHe boil-off rate of 5L / hr.

Table 8.3 Operating specifications of cryocoolers for superconducting electronic systems.

SYSTEM / PARAMETER	SQUID: ELF Antenna	SQUID: Rock Mag	SQUID: Geo Mag	SQUID: Bio Mag 1-3 ch	SQUID: Bio Mag Array	SQUID: Susceptometer	JJ Volt. Std.	JJ Computer	Microwave Recvr	Signal Processor
Cryocooler Load (W)	.05	.05	.05	.03	0.1-0.5	.4-.6	.03	0.1-10	0.1-0.2	.2-.5
Cryocooler Temp (K)*	<8	<8	<8	<8	<8	4.2	2	4.2	<10	<10
Input Power (W)	50-100	50-100	50-100	30-60	100-1000	400-1200	30-60	100-20KW 2000	100-400	200-1000
Cooled Mass (Kg)	2	4	2	2	2	15	0.5		5	5
Cooldown Time (h)	~24	5	5	5	5	24	1	10	5	5
Vibration Limitation (degrees in band motion)	10^{-9}	10^{-1}	10^{-7}	10^{-2}	10^{-2}	10^{-3}	10^{-1}	10^{-1}	10^{-1}	10^{-1}
Magnetic Noise Limitation 10^{-15}T rms/$\sqrt{Hz}$	<5	10^{9}	<5	<5	<5	10^{10}	10^{10}	10^{9}	10^{9}	10^{9}
Magnetic Shielding	No	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes
System Bandwidth (Hz)	10^{2}-10^{3}	<10	10^{-4}-10^{2}	~DC-10^{3}	~DC-10^{3}	<10	<1		10^{8}-10^{12}	10^{9}-10^{11}
MTBF (h)	10^{4}	10^{4}	10^{4}	10^{4}	>10^{4}	10^{4}	$5x10^{3}$	10^{4}	$3x10^{4}$	10^{4}
Service (h)	$5x10^{3}$	$5x10^{3}$	10^{3}	$5x10^{3}$	$5x10^{3}$	$5x10^{3}$	10^{3}	$5x10^{3}$	$1x10^{4}$	$5x10^{3}$

* For Nb devices operating well below T_c. For high T_c devices the refrigeration temperature may be in the 10-20K interval with lower cryocooler I/p power

8.2 Magnet and Cryocooler Development Plan

The technical viability of the EDS Maglev transportation system depends basically on two technologies:

(a) light weight, stable superconducting magnets
(b) light weight, efficient, ultra-reliable cryocoolers

An outline long range plan for the development of superconducting magnets and cryocoolers for the Canadian EDS Maglev vehicle was presented to TDC, and discussed as part of Progress Review Meeting #2, May 15, 1985 [2]. At the same meeting, a detailed draft proposal for the next phase of magnet developments was also submitted [14].

The long range plan was based on development of cryogenic components for the 1982 Canadian vehicle design [15] - levitation magnet, LSM magnet and a suitable cryocooler configuration. At present, the vehicle design is undergoing revision. The concept of utilizing the levitation capability of the triple solenoid LSM coils is being investigated [16]. The specific merits of this approach, besides maintaining the advantages of the unique Canadian vehicle and guideway design are

- elimination of the 6 levitation coils per car of the 1982 design
- considerable reduction of the onboard cryocooling requirement
- as a consequence, a considerable reduction of the onboard power requirement
- simpler integration problem for the cryocooler/magnet interface
- reduced vehicle section, aerodynamic drag, weight and LSM power requirement.
- potentially higher reliability, lower specific energy consumption system.

As a consequence of this ongoing refinement of the new Maglev vehicle design, and the uncertainties of time scale, the long range plan has been somewhat altered. In outline form, this is indicated in Figure 8.2, with further details in Figure 8.3.

In the overall plan of Figure 8.2, the goals will be :

a) Fabrication of a racetrack magnet with a coil of mean dimensions 1.06m long x 0.3 m end diameter with a heat exchanger in the LHe_4 reservoir. The preferred coil frame would be the 2-sided cooling structure (Fig. 3.1b).

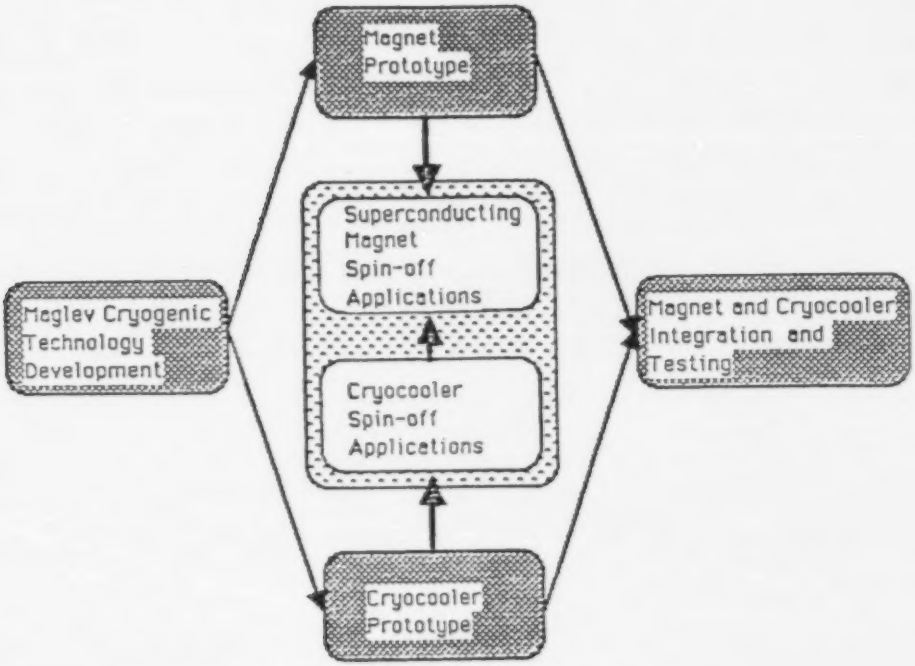


Figure 8.2: Outline of a general long range plan for development of magnet and cryocooler technology suitable for EDS Maglev vehicle.

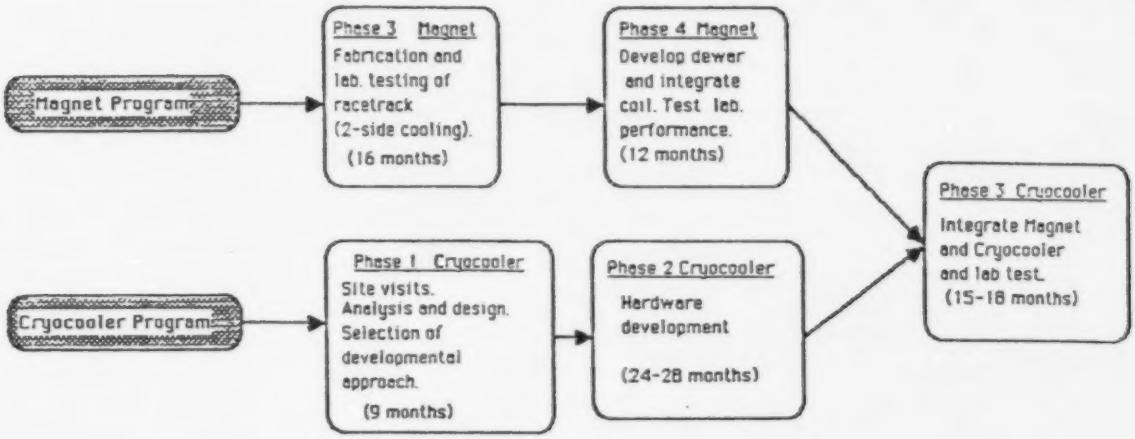


Figure 8.3: Breakdown of magnet and cryocooler programs into phases.

b) Development of a suitable cryocooler, after assessment of the requirements.

c) Integration and testing of the magnet and cryocooler.

The combined magnet development and cryocooler programs are divided into a number of milestones over approximately 4 years with initiation in July, 1986 - Figure 8.3.

Merits of racetrack magnet selection

- The racetrack coil presents the toughest test of the technology i.e. if a racetrack is sucessfully fabricated, then the probability is quite high for the successful fabrication of other magnets such as the 1m diameter LSM solenoids. The reverse is not nesessarily true.
- The racetrack represents the most efficient design. Further refinements of the Canadian Maglev vehicle may result in the design selection of racetrack LSM coils.
- Smaller scale racetracks give good insight into the behaviour of larger racetracks.
- With the present racetrack design, it will be possible to validate the 2-sided cooling both in isothermal and isochoric modes. The 2-sided cooling concept is a natural selection for the 1m diameter LSM solenoids, where the outer channel presents a very stiff light weight beam to partially restrain the Lorentz loading. (The 1.06 m mean length racetrack is equivalent to an 0.8m mean diameter solenoid).
- The racetrack coil has spin-off potential e.g. superconducting magnet drum-type separator.
- The use of a racetrack coil represents the least expensive method of fully validating the epoxy impregnation technology being developed in the present Phase 2 contract.

Merits of the Cryocooler Program

- There are considerable spin-off applications for cryocolers of capacity ≈ 1 W at 4.2-4.5K.
- EDS development emphasizes the high reliability requirement for cryocoolers. Other technologies will benefit - e.g. MRI, magnetic separators, Josephson Junction and superconductive thin film micro-electronics.

- Acquisition of cryocooler technology will considerably enhance and complement CTF's cryogenic system expertize and commercial products.

8.3 Magnet Development - Detailed Proposal for Phase 3

A schematic outline of this project, which is scheduled to commence during July, 1986 and have duration 15 months, is indicated in Fig.8.4. The basic goal is the fabrication and testing of a full scale levitation coil using the techniques developed during the Phase 2 project described in this report.

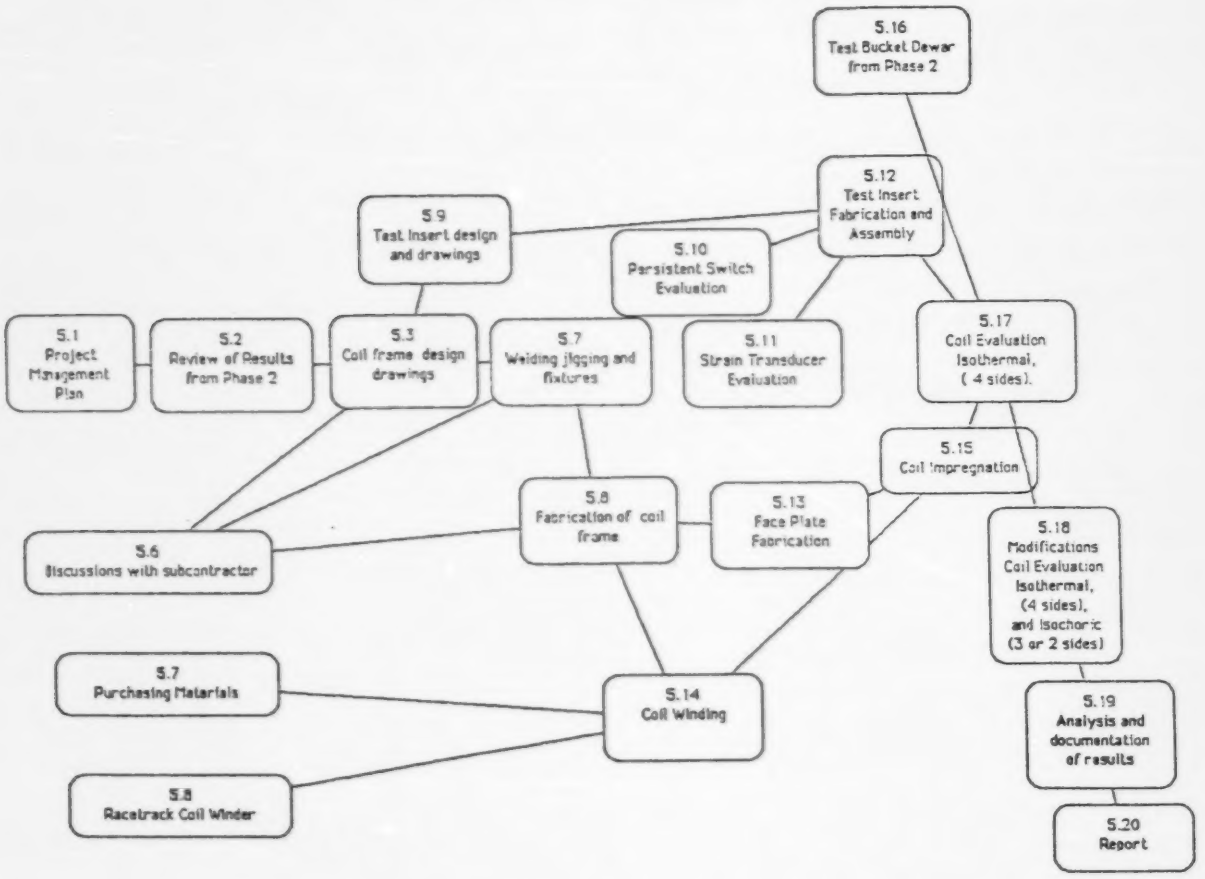


Figure 8.4: Project plan for Levitation racetrack magnet fabrication and static testing. Duration : July 15, 1986 - Oct. 15, 1987 (15 months).

9. CONCLUSIONS

The research and development described in this report encompasses the first hardware phase toward establishing a Canadian technology for lightweight, superconducting magnets suitable for the EDS Maglev system and other applications. During the contract, the following tasks have been accomplished:

1. Development of winding techniques on SS304L frames for fabrication of solenoidal and racetrack coils with fill factors in excess of 80%.
2. Establishment of effective epoxy impregnation procedures for completely filling tightly wound test solenoids and racetrack coils of the Canadian Maglev design.
3. Establishment of a test facility for investigation and characterization of superconducting coils including: an 18 inch access test dewar, a test insert, a 900 A, 5V DC current supply, and cryogenic storage and handling equipment.
4. Successful fabrication and testing by direct immersion in LHe_4 of a superconducting solenoid, at currents within 2% of the measured short sample critical current.
5. Preparation of 2 reports on the near-term spin-off benefits of EDS Maglev component development (superconducting magnets and cryocoolers).
6. Outlining a long range plan for development and testing of all the cryogenic magnet and cryocooler components for the Canadian Maglev system.
7. Preparation of a detailed proposal for the next development phase for a superconducting levitation coil of racetrack geometry.

The fabricated solenoid displayed good performance and reached the design current after one quench. The solenoid then trained up to within 2% of the short sample current after a further 7 quenches which included recooling the coil from LN_2 and also from room temperature. The manner in which the quench tests were conducted resulted in considerable energy being dissipated within the windings . The coil does not appear to have suffered any damage after being subjected to an estimated temperature rise of 100K, internal voltage drops of the order of 1kV, and (tensile) hoop stress levels to about 170 MPa. These results lend some credence to the fabrication procedures which have been developed. Unfortunately, time and budgetary constraints did not allow the fabrication of a second solenoid which would further validate the procedures.

The surveys which have been prepared on the spin-off benefits of EDS Maglev R & D have suggested that there will be considerable applications activity in superconducting magnets and closed cycle cryocoolers in the near-term. This appears especially in the production of systems which integrate superconductive components (magnets or micro-electronics) with cryocoolers of high reliability, high efficiency, and reasonable economy.

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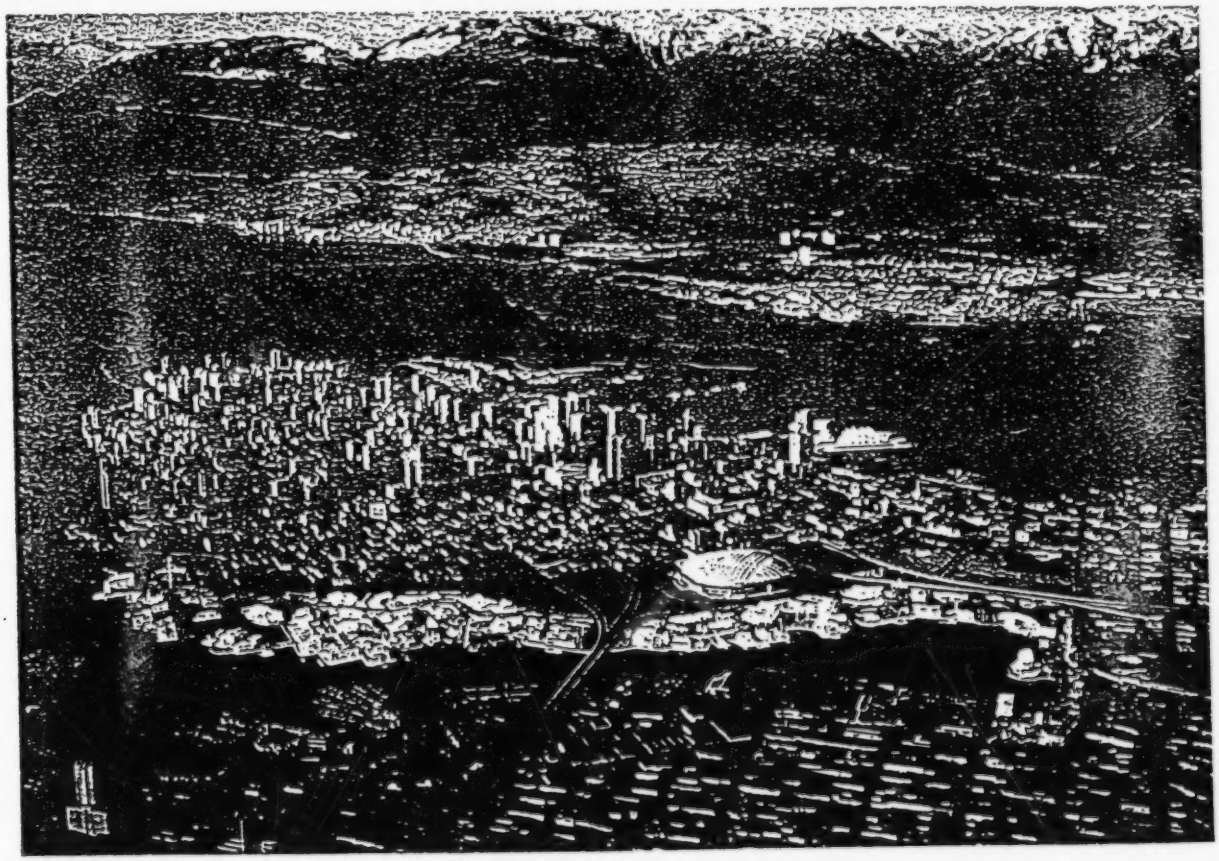
APPENDIX A

Texts of the papers presented at two conferences on Maglev:

1. Maglev Transport '85, Tokyo, 1985.
2. Maglev and Linear Drives, Vancouver, 1986

International Conference on MAGLEV & LINEAR DRIVES



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DEVELOPMENT OF SUPERCONDUCTING MAGNETS FOR THE CANADIAN ELECTRODYNAMIC MAGLEV VEHICLE

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Abstract

A review is presented on the current status of superconducting magnet developments for the Canadian electrodynamic Maglev transportation system. Various design aspects of the levitation and linear synchronous motor magnets appropriate for the current vehicle concepts, are discussed. In addition, recent experimental work is outlined on the development of a suitable epoxy impregnation technology for the superconducting coils.

Introduction

A high speed electrodynamic (EDS) Maglev system has been proposed as a future transportation alternative for the 600 km Toronto-Ottawa-Montreal traffic corridor. Research and development of this advanced guided ground mode has been active in Canada since the early 1970's under the sponsorship and co-ordination of the Transportation Development Centre of Transport Canada. The system design has evolved through contributions from an interdisciplinary team of researchers drawn from several Canadian universities (Queen's, Toronto and McGill), from government laboratories (National Research Council), and from industry (CTF Systems Inc.). A recent overview summarizes the objectives and achievements of the program [1].

The severe winter conditions which prevail in the proposed corridor during a significant part of the year, have dictated the choice of the EDS Maglev mode. The central features of the Canadian design include electrodynamic suspension with air-core linear synchronous motor (LSM) propulsion, integrated with "null flux" guidance. Operation on an elevated flat-topped guideway is predicted to enhance removal of dry snow accumulations by action of the prevailing cross wind.

The original baseline system design [2], has undergone extensive revision, following a detailed economic comparison of the Maglev mode with 260 km/hr electrified rail, and short-haul passenger air transport [3,4,5]. The present Canadian Maglev system (Fig. 1) consists of two-car, bi-directional train sets designed to operate at a cruise velocity of 450 km/hr on an elevated box-shaped guideway with aluminum levitation strips on the top surface, and LSM stator and "null-flux" windings on the box sides. This updated design features reduced capital costs and specific energy consumption, with improvements in operational reliability, safety and servicing.

In addition to alteration of the guideway design, there have been significant changes to the vehicle and cryogenic components. Changes to the latter include the selection of NbTi superconducting coils isothermally cooled by on-board cryocoolers, rather than Nb_3Sn windings cooled isochorically [6]. Also, each car has

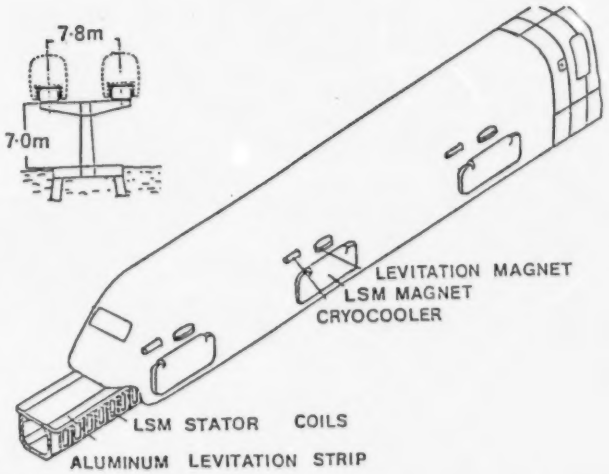


Fig. 1 Outline of 1982 Canadian EDS Maglev vehicle and guideway design indicating location of superconducting magnets and cryocoolers.

nine LSM solenoids per side, mounted in sets of three per cryostat. The triple solenoid LSM and levitation magnets are coupled to a closed cycle cryocooler and the three components form a module which can be removed for servicing purposes. A further evolution of the design which is presently under consideration, is the elimination of the levitation magnets and either relocation of the guideway aluminum strips or introduction of guideway coils to provide levitation via electrodynamic interaction with the LSM coils. This development would simplify the magnet and cryocooler configurations and reduce the vehicle specific energy consumption.

On-board system technologies which require considerable further development include those for:

(a) stable, lightweight superconducting magnets
(b) high reliability, lightweight closed cycle cryocoolers.

A recent objective of the Maglev program has been to establish within Canadian industry, a superconducting magnet technology suitable for the vehicle designs. Following detailed analyses and design of a prototype levitation magnet [7] , the program has advanced to a hardware phase involving studies and fabrication of epoxy impregnated coils.

In the following sections, prototype magnet designs for the EDS Maglev operation will be summarized. These discussions will then be followed by a description of epoxy impregnation studies for superconducting

coils, together with recent results.

Magnet Design

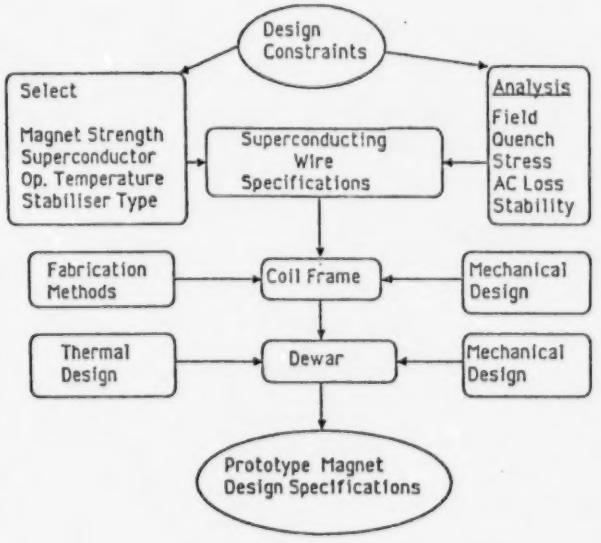
Superconducting magnets for EDS Maglev operation must have the following attributes:

- safe, quench free, stable response under all operational conditions
- minimised weight
- minimised heat load
- efficient coupling to on-board cryocooler(s).

From analyses and modelling of the proposed system, a set of design constraints has been established for both the levitation and LSM coils [1,2,4] . For the 1982 vehicle concept (Fig. 1), these are listed in Table 1.

The design approach for the present application is indicated in the flow chart of Fig. 2. Features include

(a) specifications for the superconducting wire
(b) coil frame design
(c) dewar design.



ig. 2 Superconducting magnet design approach

The primary problem to avoid in all superconducting magnet operation is that of premature quenching. Due to the extremely low heat capacity of the coil materials at 4.2K ($\approx$1mJ/cm^3/K, small quantities of heat input can easily trigger a quench. The dominant source of this quench-inducing heat is thought to be mechanical disturbances within the coil matrix, caused by the combination of winding, cooldown and Lorentz stresses (e.g. wire motion, micro-fractures, etc). With magnet strengths appropriate for EDS Maglev (400-1000 KAT), the most common technique for coil fabrication is to restrain the wire motion by epoxy impregnation. Numerous research groups have indicated that, while not universally successful, this approach can be optimised by careful attention to coil support and fabrication techniques.

Coil Analysis

Modelling of the proposed levitation and LSM coils has been carried out in order to determine the effects on the coil performance of variations in geometry, fill factor, wire stabiliser materials and ratio, and operating temperature. Of prime interest have been estimates of peak stress levels within the epoxy impregnated windings, and also the post-quench coil behaviour.

As an example of the temperature and field constraints on coil design, NbTi wire current densities vs. field at several temperatures are indicated in Fig. 3, where the following are plotted:

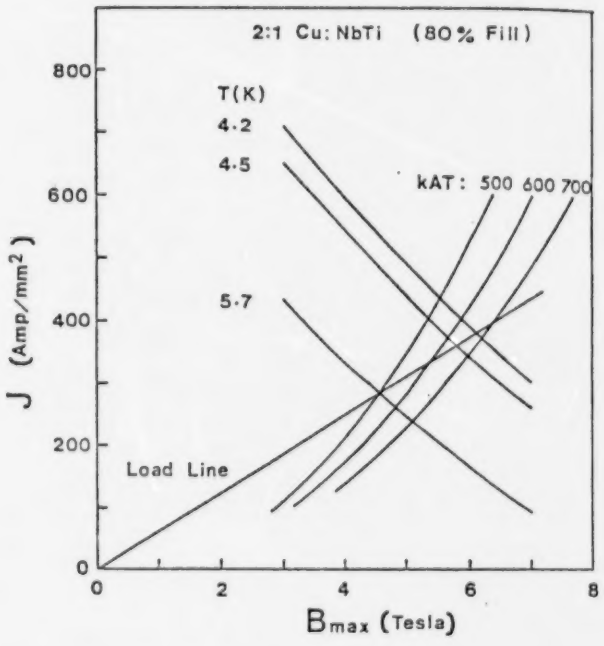


Fig. 3 Current density vs. field and temperature for 2:1 stabiliser: NbTi. Also included is the variation of J and B for square section solenoids of mean diameter 1.0m and strengths 500, 600 and 700 KAT.

(a) NbTi properties for 2:1 stabiliser: NbTi ratio at T=4.2K, 4.5K and 5.7K with an 80% coil fill factor [8];
(b) current density (J) vs. maximum field (B_{max}) for square section solenoids of mean diameter 1.0 m and strength NI=500, 600 and 700 kAT;
(c) coil load line with J=280 A/mm^2 at T=5.7K

The temperature of 4.5K is taken as a typical operating temperature for a magnet coupled to a closed cycle cryocooler, and 5.7K can be used to define both an operational temperature margin and a helium reservoir capacity for 1.5 hours of isochoric operation, in the event of on-board cryocooler failure.

Circumferential, radial and axial stress levels within the impregnated windings have been computed for variation of the coil section from square to rectangular. As an example, total peak circumferential stress levels at the coil median point (σ_M) are plotted in Fig. 4 with variation of radial width (A) from 2 cm to

Table 1: Magnet Design Constraints and Goals

Parameter	Levitation	LSM
Coil Type	Racetrack	Triple Solenoid
Mean Dimensions (m)	{Length: 1.06 {End radium 0.15	Diameter: 1.0
Coil Strength (Ampere Turns)	400,000	500,000
Superconductor	Multifilamentary NbTi	Same
Max. Envelope (m x m x m)	0.52 x 0.85 x 1.46	Minimised
Magnet operation	Persistent Mode <3% rundown in 16 hrs	Same
Quench Protection	Coil self-protecting	Protection by dumped resistor
Coil Cooling	Isothermal with reservoir heat exchanger	Same
Helium Reservoir	Capacity for 1.5 hours of isochoric operation	Same
Cryostat Heat Load	<15 watt to 77K < 5 watt to 4.5K	<35 watt to 77K < 5 watt to 4.5K
Weight (Kg)	100	500

8 cm for an LSM solenoid with mean diameter 1.0 m (NI=500 kAT, T=5.7K). These stress estimates include a constant winding tension of 8kg, thermal contraction effects and Lorentz loading. Also included is the variation in σ_M for copper stabiliser ratios from 1:1 to 2:1.

Some conclusions from the analyses related to field, temperature and stress levels are as follows.

(a) One can minimise the conductor weight for a given fill factor at the expense of increasing the current density and the resulting peak stress levels.

(b) Variation of the coil section from square to rectangular with aspect ratio 2 or 1/2 decreases the conductor weight by ≈ 10%, while increasing σ_M by a similiar amount.

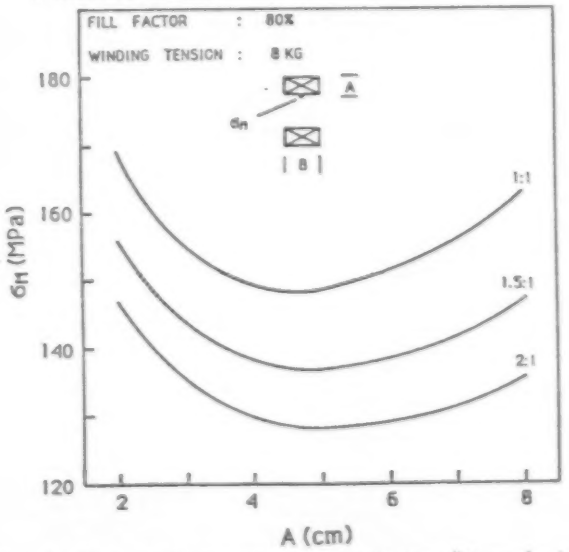


Fig. 4 Estimated variation of total peak circumferential stress with radial thickness A, for rectangular section NbTi solenoids using copper stabiliser ratios 1, 1.5 and 2 on the T=5.7K line (NI=500 kAT, mean diameter = 1.0m)

(c) For the present levitation and LSM magnet configurations (Fig. 1), coils with a pancake aspect ratio are preferred using arguments of minimum weight and maximum magnetic loading efficiency (minimum distance to the drive coils and levitation strips). However, relative to square sections, these shapes have higher peak stress levels, lower stiffness, and may have cooling problems with some of the coil frames under consideration (see Fig. 7). Thus square section windings have been selected as a reasonable compromise for levitation coils. For the LSM coils, σ_M levels were found to be similar for equal area, square and rectangular sections with aspect ratio B/A=2. Coil cooling will be superior with the latter, and thus rectangular sections with this aspect ratio are preferred for the prototype LSM windings.

In order to model the effects of coil geometry, fill factor, and stabiliser on the post-quench coil response, use has been made of the QUENCH software developed by the Rutherford High Energy Laboratory group [9,10]. QUENCH allows estimation of two key parameters: (a) T_{max}: post-quench peak temperature and (b) V_{max}: post-quench peak internal voltage. In order to avoid coil damage by excessive thermal stress or insulation breakdown, the coil and protection devices are usually designed such that T_{max} is $\lesssim$ 100 K and V_{max} $\leq$1.0-1.5 kV.

In Figs. 5(a) and 5(b), estimates of T_{max} and V_{max} for the levitation racetrack are plotted as a function of stabiliser: NbTi ratios over the range of 1:1 to 6:1. These data were generated for square section levitation coils with NI=400 kAT with the total coil energy of ≈110kJ dissipated in the coil and helium. The stabiliser materials considered were copper, aluminum and the aluminum clad copper system developed by intermagnetics General of the USA [11]. For example, with 100% of the quench energy dissipated in a 2:1 Cu:NbTi coil, the peak temperature estimate was ≈ 85K, and peak voltage ≈ 900V. These values can be lowered through appropriate selection of protection and persistent switch resistances. The 1.0 m diameter LSM solenoids have been analysed with similar conclusions.

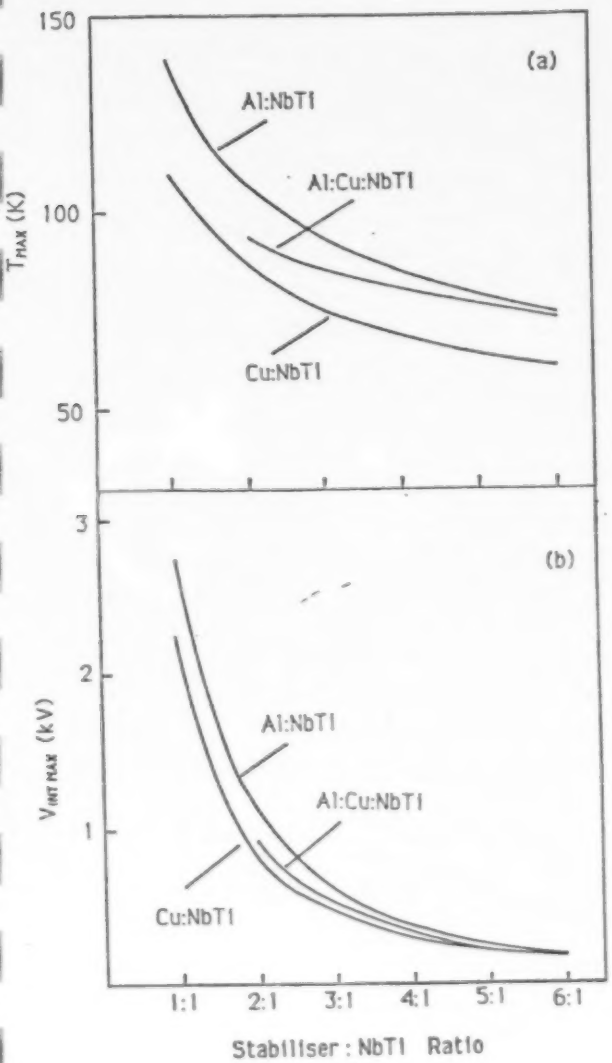


Fig. 5 (a): Estimated maximum post-quench temperature as a function of stabiliser ratio for the levitation racetrack using copper, aluminum, and aluminum+copper stabilisers.

(b): Estimated maximum post-quench internal voltage as a function of stabiliser ratio. (For Al:Cu:NbTi, the Cu:NbTi ratio is maintained at 1:1).

Estimates have also been made of the coil stability against quenching, using the "minimum propagation zone" model [10]. Figure 6 compares the minimum quench energy (E_{min}) as a function of the reduced current I/I_c for a square section levitation coil with various stabilisers and ratios. It is clear that as the critical current is approached, minute quantities of energy input can initiate the quenching process.

Some conclusions from the quench and stability analyses are as follows.

(a) For 100% energy dissipation internally, there are marked increases in V_{max} and T_{max} for stabiliser ratios <2:1. As the stabiliser ratio approaches 1:1, it becomes necessary to dump some of the coil energy externally in the protection resistor.

(b) For a given stabiliser ratio, the use of aluminum rather than copper increases T_{max} and V_{max} by ≈25%;

(c) The use of aluminum stabiliser projects a stability advantage of at least one to two orders of magnitude over copper stabilised wire. However this may be difficult to achieve in practice, due to the fact that the conductivity of high purity aluminum is susceptible to strain induced degradation.

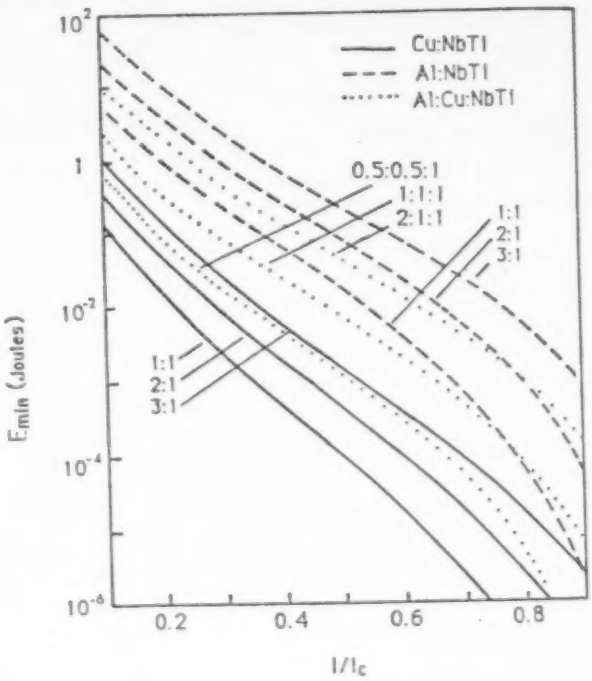


Fig. 6 Estimated minimum quench energy (E_{min}) for the levitation racetrack versus reduced current I/I_c for several stabilisers and ratios (I_c = critical current).

Upper limits on wire sectional area and filament diameter are determined by the adiabatic and dynamic stability criteria [10]. A relatively large wire is preferred in the Maglev application due to the goal of a large coil fill factor and a stiff coil structure. For the first prototype coils, NbTi wire with copper ratio 2, section 2mm x 1mm, and minimum filament number ≈450 has been selected.

Coil Frame and Dewar Designs

The coil frames for the levitation and LSM magnets are designed to (a) function as a frame during coil fabrication, (b) efficiently cool the composite, (c) support and restrain the internal loading, and (d) rigidly transmit the external electromagnetic loading to the outer dewar and vehicle via suitable structural supports. An example of a prototype frame for a racetrack levitation coil is outlined in Fig. 7. This design is an adaptation of the concepts of Mine et al [12]. The coil is wound on the central channel, which is then sealed and the coil impregnated with epoxy.

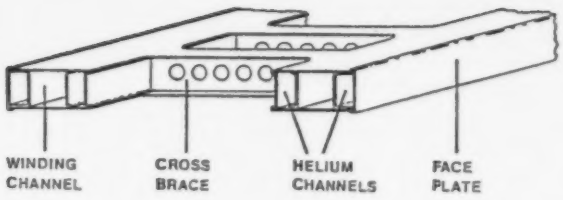
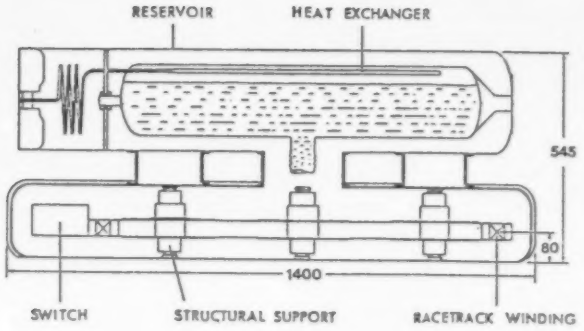
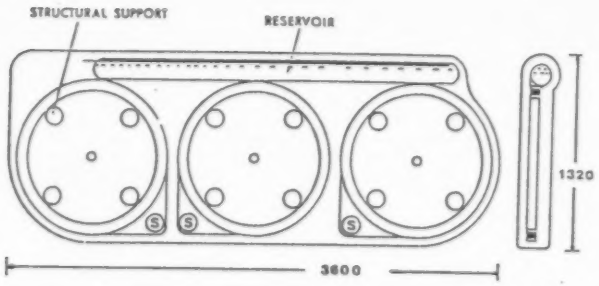


Fig. 7 Coil Frame Design



(a) Levitation Magnet



(b) LSM Magnet S = Persistent Switch

Fig. 8 Magnet Outlines: (a) Levitation (b) triple solenoid LSM. Dimensions in mm.

The inner channel allows direct cooling of the most severely stressed coil composite elements, and the outer channel performs the dual functions of coil cooling and restraint of the lateral or radial loads. This frame design concept can be employed both for racetrack and solenoidal magnets.

Outlines of the complete cryostat design for the prototype levitation and LSM magnets are indicated in Figs. 8(a) and 8(b) respectively. The levitation magnet design has been slightly altered from the version presented in [1], with a reduction in reservoir capacity to 25 litres. This is consistent with isochoric operation for 1.5 hours, and provides some safety margin for a 4.5K heat load of about 2 watt. Lighweight lithium-aluminum alloys are proposed for the helium reservoir and outer hull in order to reduce system weight. The LSM magnet design (Fig. 8(b)) utilizes the coil frame design of Fig. 7, and has the helium reservoir integrated within the main dewar envelope. Four columnar structural supports mount each solenoid to the dewar outer hull and hence to the vehicle. A single pair of gas-cooled current leads is used to energise the three solenoidal coils which are shorted by separate, thermally operated persistent switches. Estimated heat loads and weights for these magnet designs are indicated in Table 2.

The magnet refrigeration system is a combination of flowing LN_2 coolant plus coupling of a 4.5K cryocooler of capacity about 5 watt to the heat exchangers, which are built into each magnet reservoir. One cryocooler per LSM/levitation magnet pair is the preferred configuration. From the present estimates, a 40% reduction of on-board cooling requirement is expected, if the levitation magnets are eliminated.

Table 2: Heat Load and Weight Estimates for Prototype Magnet Designs

Item	Levitation	LSM
Copper:NbTi Ratio	2	2
Operational Current Density (A/mm^2)	250	280
Heat Load (W)		
to 77 K	7	25
to 4.5 K	2	3
Weight (kg)	115	550

Epoxy Impregnation Study

Prior to the fabrication of superconducting coils, an investigation was conducted into the penetration properties of specific epoxies in densely packed magnet windings. The following have been of interest in these studies:

(a) experimental coil fill factors for differing wire and mold geometries;

(b) development of techniques for minimising void content while maintaining a high coil fill factor ($\geq 80\%$);

(c) coil behaviour on cool-down to cryogenic temperatures.

Several epoxy systems were investigated, and the basic approach involved:

(a) measurement of the epoxy and hardener viscosity as a function of time and temperature;

(b) estimation of the optimum impregnation temperature to maximise channel penetration.

After the selection of an appropriate epoxy mix, model coils of insulated copper magnet wire were fabricated, and impregnated with the system outlined in Fig. 9. The coil, sealed in its mold, was heated under vacuum in a temperature controlled oven for about 10 hours prior to impregnation. In the oven, the coil and mold

temperature stability was ±1 C/hour. After reaching thermal equilibrium, the epoxy container was pressurized and the epoxy driven into the winding. The epoxy was allowed to flow through the system for 10-15 minutes after reaching the coil exit. The coil composite was then cured at elevated temperature and pressure to minimise any void volumes. After curing, the mold was dismantled and the coil composite removed for inspection.

Variables of the process included:

(a) impregnation temperature
(b) wire sample and geometry
(c) coil sectional area and geometry (solenoidal and racetrack)
(d) wire layer spacer thickness.

A typical coil section for a round wire solenoid is indicated in Fig. 10 with an interlayer fibreglass spacer clearly visible (fill factor ≈ 70%). No voids were visible at the resolution limits of the microscope. Coils fabricated without the spacer tended to have dry volumes in the centres of the coil sections.

A full scale model levitation racetrack mold and coil with mean dimensions as in Table 1 have also been fabricated. The mold and sectioned impregnated winding are indicated in Fig. 11. The coil was wound with 2mm x 2mm insulated copper wire and a fill factor of ≈80% was achieved with minimal void content.

Cryogenic tests of the model coils included multiple cycling of the coil plus mold between 300 K and 77K. This was followed by sectioning of the winding and microscopic inspection for thermal damage. No damage to the coil composite bulk material has been observed for 8 test coils which had fill factors > 70%. However, regions on the coil surface which were epoxy rich tended to fracture after about 5 thermal cycles.

Superconducting Coil Fabrication and Results

A superconducting solenoid of mean diameter 30 cm and square section of side 4 cm, has been fabricated utilizing the procedures established for the copper wire coils. The coil frame is similar in form to Fig. 7, and has been designed to investigate the stability of the coil against quenching when the cooling is changed from total immersion in liquid to partial cooling on two or even a single side. The latter approaches are of some interest, since the coil frame weight can be reduced.

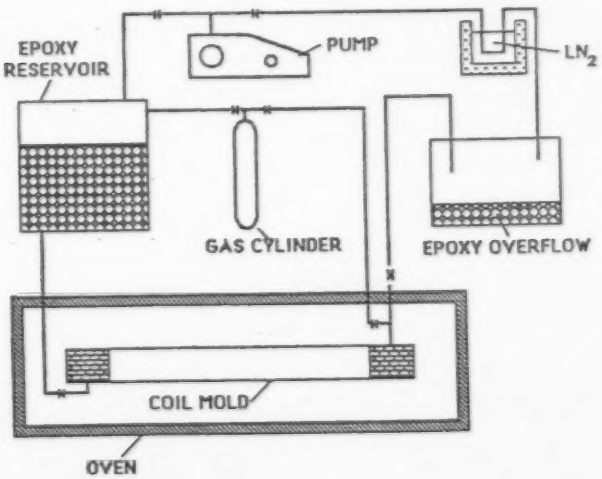


Fig. 9 Epoxy Impregnation System

Tests on this solenoid have been carried out in an instrumented test dewar. The data for repeated quench tests while totally immersed at 4.2K are outlined in Fig. 12. This coil displayed minimal training and exceeded the design current density (250 A/mm^2) after the first quench. A peak current density of 326 A/mm^2 has been reached, which represents 90% of the critical value (peak magnet strength = 495 kAT). Further tests on this coil and similar prototypes will be reported at a later date.

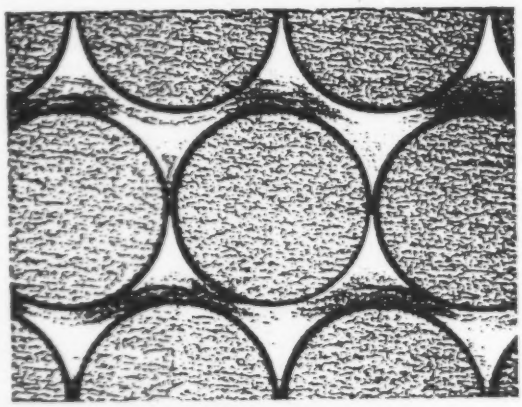


Fig. 10 Sectioned impregnated winding (copper wire)

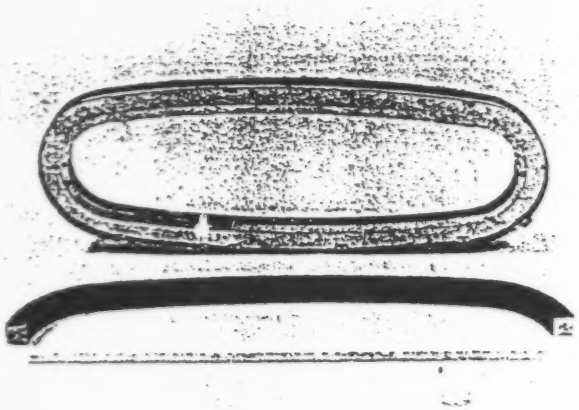


Fig. 11 Model levitation racetrack mold and epoxy impregnated winding section (copper wire)

Conclusions and Future Plans

In this paper, analyses and designs have been presented for levitation and LSM magnets for the Canadian EDS Maglev vehicle. Progress has also been reported on the development of a magnet fabrication technology suitable for the EDS Maglev application. The results from the first of a series of superconducting coils are promising. In the near future, the solenoid technology will be extended toward fabrication of a coil of racetrack geometry and dimensions similar to the current levitation coil design.

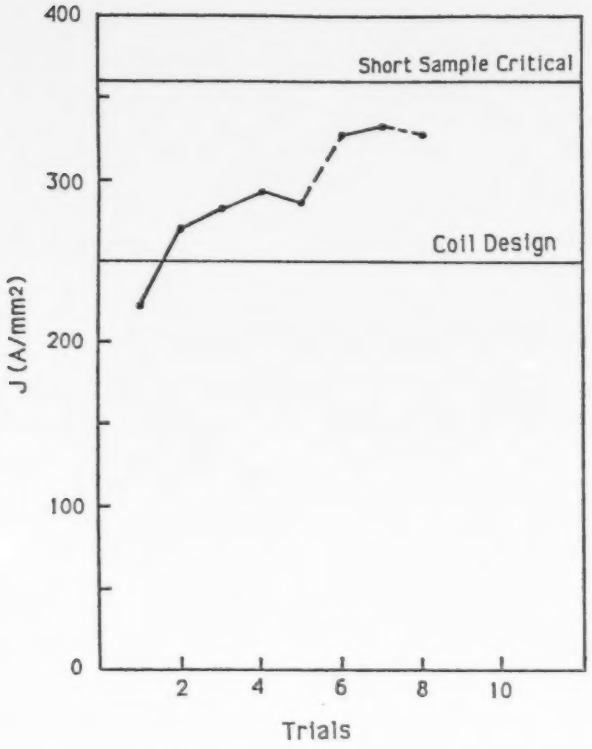


Fig. 12 Repeated quench tests at 4.2K for an epoxy impregnated solenoidal coil of mean diameter 30 cm, and square section of side 4 cm (copper stabiliser ratio 2). The dashes indicate warming to 77K between trials.

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AN OVERVIEW OF CANADIAN MAGLEV RESEARCH AND DEVELOPMENT

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ABSTRACT

An overview is presented on Canadian Maglev research and development. A program has been active in Canada since the early seventies and this paper focusses on the aspects of past, current, and future activities, related to the objectives and achievements of the program, the governmental perspective on Maglev development, the most recent vehicle and guideway design and optimization, and progress toward the industrial development of critical cryogenic components.

INTRODUCTION

Maglev systems represent an innovative guided ground transportation technology which promises to provide socially acceptable inter-city travel at speeds in excess of 400 km/hr. From consideration of transit time, convenience and energy usage, these systems are projected to be competitive with passenger aircraft at least for distances up to about 1000 km. Two Maglev options - the electrodynamic (EDS) and the electromagnetic (EMS) - are being developed in several countries to circumvent limitations imposed by current travel modes (aircraft, conventional train, bus and automobile).

In most Canadian traffic corridors, the personal automobile accounts for the largest percentage of passenger traffic. However, economic projections for the next two to three decades indicate a progressive shift toward a guided ground mode having the attributes of frequent service, short trip time and modest ticket costs. Within the context of Canadian Maglev developments, the severe winter conditions prevalent in the proposed 600 km Toronto-Montreal corridor (Fig. 1), have favored the EDS option. The large vehicle guideway clearance makes winter operation feasible and potentially reduces the guideway constructional precision and hence the initial capital costs.

The Canadian Maglev program, is a long range R. & D. undertaking aimed at the optimal deployment of non-contact transportation technology, within the framework of Canadian requirements. Since its inception, the program has been supported by the Transport Canada Research and Development Centre (TDC) with additional sponsorship by the National Research Council of Canada (NRC). An inter-disciplinary group of researchers, drawn from several Canadian universities (Queen's, Toronto and McGill), NRC, and industry (CTF Systems), have contributed to fundamental studies, component and system designs, and an economic assessment for implementation of a complete revenue operation. With the pace of developments dictated by the desire to provide the Canadian public with an efficient, modern transport service, but moderated by the adequacy of current demand and energy pricing, the program has now advanced into an industrial phase aimed at the hardware development of critical cryogenic components. One key element is the establishment of a superconducting magnet technology suitable for the Canadian Maglev vehicle design. This paper presents a review of the objectives, achievements and status of the overall program with an emphasis on current developments, and a discussion of future plans.

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PROGRAM OBJECTIVES AND ACHIEVEMENTS

A primary objective of the Canadian Maglev program up to this time, has been the definition, refinement and economic evaluation of an appropriate EDS Maglev system. It was recognized in the seventies, that the deployment of a revenue Maglev system within the proposed corridor may not be feasible until the early years of the 21st century. This conclusion has been reached through consideration of a mix of projections involving passenger traffic densities, availability of oil, and technical and economic factors. Nevertheless, it has been considered a suitable strategy for Canada to maintain a modest level of research and development in this technology, in order to gain the expertise necessary to exploit Maglev technology when the need becomes apparent, and in the expectation of near-term spin-off benefits both to transportation and other emerging technological areas (1).

The historical evolution of the Canadian program is summarized in Table 1, which includes both the activities and the major participants. In itemized form, the objectives and achievements can be listed as follows:

(i) The development of a nucleus of Canadian researchers in universities, government and industrial laboratories, familiar with Maglev through analysis and experimentation, to aid the federal government planning relative to the Maglev transportation option.

(ii) The establishment of test facilities for Maglev component development and evaluation. The most notable is the 7.6 m diameter test wheel operated by the Canadian Institute of Guided Ground Transport (CIGGT), at Queen's University. As part of the industrial development phase, a fabrication and test facility for superconducting magnets is being established at CTF Systems Inc.

(iii) The development of the technical design specifications for a high speed, revenue EDS Maglev system. Following fundamental studies for component and system definition, a baseline design has been generated (2). This basic design has been recently updated (3) (see section - System Design).

TABLE 1 Maglev Program Historical Perspective

Year	Activity	Participants
1968	Conception of Canadian Maglev program	Ferranti-Packard
1970	Preliminary design and analysis completed Foundation of CIGGT at Queen's University Formation of Canadian Maglev group Test facility concept developed Detailed analysis and design of sub-systems	Queen's Univ. Toronto Univ. McGill Univ. CIGGT
1972	Test Wheel design completed	CIGGT
1974	Test facility fabricated and commissioned LSM propulsion demonstrated and tested LSM tests completed and control modes evaluated	CIGGT CIGGT CIGGT
1976	Electrodynamic suspension tests completed Detailed system conceptual design initiated Engineering studies of Maglev system completed Economic assessment initiated	CIGGT NRC NRC/CIGGT (2) CIGGT
1978	Modelling of levitation coil moments and forces	McGill Univ.
1980	Economic assessment completed Industrial participation initiated Isochoric cooling study completed	CIGGT (4) CTF Systems CTF Systems
1982	Vehicle design concept revised	NRC (3)
	Levitation magnet design study completed	CTF Systems (7)
1984	Technical assessment completed Superconducting magnet development initiated Los Angeles - Las Vegas Maglev technology assessment initiated	NRC CTF Systems CIGGT/NRC

(iv) The development of economic modelling for transportation projections. For the proposed Toronto-Montreal traffic corridor, CIGGT has completed an evaluation of the comparative merits of intermediate speed rail (ISR), high speed rail (HSR), Maglev and passenger aircraft (4). This economic study has indicated that implementation of a revenue Maglev operation in the corridor is unlikely before the year 2000.

(v) The exploitation of spin-off benefits for currently deployed technology. Areas include:
- application of a.c. linear motors to automated urban transit
- microprocessor controlled rotary drives for railway locomotives

(vi) The exploitation of spin-off benefits associated with Maglev cryogenics technology. Areas of growing interest include:
- application of superconducting magnets
- applications of associated cryocooler

technology.

Superconducting magnet applications are evolving at an accelerating rate. Areas of interest to government agencies, high technology companies, and the medical community, include medical resonance imaging (MRI), magnetic separation (coal de-sulfurizing, ore enrichment, chemical purification), marine motor propulsion, a.c. and magneto-hydrodynamic power generation, power conditioning and energy storage. The expanding applications of superconductors are highlighting the need for ultra-reliable, efficient, closed cycle cryocoolers for long-term, stable maintenance of these superconducting systems at their operating temperatures. The development of cryocoolers for EDS Maglev operation is generating interest from other applications areas such as superconducting micro-electronics.

CANADIAN MAGLEV SYSTEM DESIGN

The Canadian EDS Maglev System is based on electrodynamic suspension with air-core, linear synchronous motor propulsion integrated with "null-flux" guidance. Recently the initial baseline design (2), has been extensively revised in order to reduce system capital costs and specific energy consumption, and also to improve operational reliability, safety and ease of servicing (3). Two-car Maglev train sets, of capacity 276 passengers, are now considered to provide the appropriate level of service. Operating at 450 km/hr, the system offers Toronto-Montreal trip times of 95 minutes with utilization projected at 10-12 million passengers per year in 2010.

Unlike the inverted U-shaped guideway favored by the Japanese National Railways, the Canadian vehicle is now designed to operate on a box shaped guideway, with levitation strips on the top surface and with the synchronous motor stator and "null-flux" guidance coils mounted on the side surfaces as indicated in Fig. 2(i). The guideway has elevation typically 7 m, and has dual tracks for the bi-directional 2-car train sets (Fig. 2(ii)). The guideway design is largely dictated by the necessity of avoiding excessive snow and ice accumulation on the running surfaces during the six month winter operating period. The train is 56 m long with an operational mass estimate of 59 tonnes. Per car, there are six racetrack levitation magnets and six triple solenoid LSM pods. Details of the levitation magnets are summarized in Table 2 with a detailed description of the system in Ref. 3. Key features of the updated system design are:

- effective dry snow clearance from the guideway for cross-winds above 8 km/hr
- 30% improvement over the original design (2) in specific energy consumption (to 93.2 watt-hr/seat-km)
- capital cost savings via simplified guideway, simplified (solenoidal) LSM superconducting windings, non-overlapped stator windings, and integrated LSM stator and "null-flux" windings
- elimination of vehicle resonance effects associated with guideway beam deflection
- novel vertical guideway switch to divert trains to wayside stations
- integrated modular approach to cryogenic cooling for the LSM and levitation coils
- less than 80 gauss whole body magnetic field exposure in the passenger compartment without ferromagnetic shielding
- on-board power supplied either by a gas turbine or linear generator at cruise, and a "third rail" at low speed.

The low (d.c. and a.c.) magnetic field exposure for passengers, is a potential advantage in light of the recently reported biological effects of magnetic fields (5).

In order to improve reliability and ease of service, the coupled cryocooler (with compressor) and the levitation and LSM magnets are mounted together in a "magnet module" which can be readily removed for servicing. For the current generation of LSM and levitation magnet designs, the combined heat load to 4.2 - 4.5 K has been estimated to be in the range 6-7 watts. For the Canadian Maglev design, a number of suggestions have been made for cryocooler type:

- an integrated Giffard-McMahon cycle and Joule-Thomson expansion loop;
- a Claude cycle system which utilizes expansion

turbines with helium gas bearings.

Considerable developmental efforts remain in this area. Cryocooler systems, which are compact, reliable and efficient would now appear to be the major focus for EDS Maglev research. On a broader front, there is world wide activity toward development of closed cycle cryocoolers for operation of superconducting devices, principally superconducting magnets and Josephson Junction micro-electronics. Refrigeration powers of interest range from ≈ 0.1-10 watts for liquid helium temperatures. Extensive research programs are being under taken to tackle many problems associated with small cryocoolers, including cycle analysis, regenerator development for temperatures in the range 4K to 15K, heat exchangers, and non-contaminating lightweight compressors. Successful solutions to these problems will have a beneficial impact on the long term viability of EDS Maglev transportation.

MAGNET DESIGN

Levitation Magnet Design Requirements

The superconducting LSM and levitation magnets for a revenue electrodynamic Maglev system operating at a cruise velocity of 450 km/hr must be optimized for a) maximum reliability, b) maximum strength-to-weight ratio , c) maximum propulsion and levitation efficiency, and d) minimum heat load consistent with a), b) and c).

Research studies on the Canadian Maglev system conducted prior to the present industrial development phase, have established a number of guidelines for the levitation magnet and coil cooling parameters. A summary of the design constraints and goals is given in Table 2.

Coil Analysis

Many trade-off considerations enter into the design for a given magnet application. Coil analysis involves optimizing the choice of wire specifications in order to avoid problems related to flux jump instability, premature quenching, stress, and AC induced heating loss. Initially, for the given coil geometry, one selects the operational current density using known superconducting wire properties. As an example, the current density (J) versus peak field (B_{max}) for square section racetrack coils of magnet strength 400,000 Amp-turns, is plotted in Fig. 3. Also included are the coil load line, and the properties of 2:1 Cu:NbTi at 4.2 K and at 5.7 K, modified for an 80% coil fill factor. The indicated operating point represents a current density of 250 Amp/mm^2, a value which is 68% of the maximum at 4.2 K and 86% of the maximum at 4.5 K (a potential operating temperature with the magnet coupled to a closed cycle cryocooler).

Analyses were carried out to predict the coil behaviour after initiation of a quench. Both square and rectangular coil sections were considered, with copper, copper-aluminum, and aluminum-only stabilized wires. In comparison with copper stabilizer, aluminum was found to give higher quench induced peak temperatures (+25%), higher internal voltages (+20%), much higher minimum quench energies (a factor of 100), and significantly reduced conductor weight (at least a factor of 2). The improved minimum quench energy and conductor weight suggest that aluminum stabilized NbTi wire is a good candidate for superconductive Maglev applications. However, since very little experimental information was available on the performance of appropriate commercial aluminum NbTi conductors (e.g. strain induced degradation), copper stabilized wire was recommended for the first Canadian prototype coil.

Quench induced peak temperatures and peak internal voltages were evaluated with variation of coil parameters such as fill factor, aspect ratio, wire size and wire stabilizer ratio. The desire to maintain peak temperatures less than 100 K, and peak internal voltages less than 1kV, while maintaining a high coil fill factor, resulted in a wire size selection of 2mm x 1mm for 2:1 Cu:NbTi, leading to a coil current of 625 Amp at the operating point of Fig. 3.

TABLE 2 Comparison of Prototype Magnet Specifications and Design Constraints

Parameter	Design Constraints and Goals	Prototype Magnet Specifications
Coil Dimensions (m):		
- Mean Length	1.06	1.06
- Mean End Radii	0.15	0.15
- Section (80% fill factor)	0.04 x 0.04	0.04 x 0.04
Magnet Envelope (m x m x m)	< 0.52 x 0.85 x 1.46	0.52 x 0.65 x 1.37
Magnet Strength (Amp-turn)	400,000	400,000
Superconductor	Multifilamentary NbTi	2:1 Cu:NbTi. Size: 2mm x 1mm
Operational Current Density (A/mm^2)		250
Maximum Operational Temp. (K)		5.7
Magnet Operation	Persistent mode < 3% decay in 16 hours	Persistent mode. Joint Res. < 2×10^{-7} ohm
Quench Protection	Coil and switch self protecting	Max. coil temp. after quench ≈ 90 K
Coil Cooling	4.2 K isothermal with heat exchanger	4.2 K isothermal. Cooling on 3 or 2 sides (Reservoir heat exchanger)
Cryostat Heat Load: to 77 K	< 15 watt	7.5 watt
to 4.2 K	< 5 watt	2.5 watt (persistent mode)
Helium Capacity	Sufficient for 3 hrs isochoric operation	35 litres
Magnet Weight (kg)	100	120 (no cryogens) 128 (operational)

Coil Frame Design

Various coil support frame designs were considered and a comparison was made of trade offs between a) weight b) coil-guideway separation c) mechanical rigidity and strength d) ease and economy of fabrication e) potential for vacuum leaks and ease of repair. Two design variations are indicated in Fig. 4(i) and 4(ii). The idea of rigidly integrating the coil winding frame with the helium cooling channel(s) stems from the work of Mine et al (6). In the design of Fig. 4(i) epoxy impregnated windings occupy a square U-channel and are cooled on three sides by a second U-channel welded to the first at the outer corners. The winding channel along the slightly curved sides of the racetrack is sealed by a lightweight face plate whose stiffness can be tailored to match the lateral Lorentz force density variations. The expansive Lorentz forces along the coil sides are restrained by suitably dimensioned cross braces. In the design of Fig. 4(ii), the impregnated winding is cooled on two sides only. The inner helium channel cools the regions of maximum coil stress and the outer channel performs the dual functions of coil cooling and restraining the lateral Lorentz loading. In addition, the windings can be brought closer to the outer dewar wall, an important consideration in maximizing the efficiency of the levitation and LSM magnets for the Canadian vehicle design. Nitrogen strengthened stainless steel appears to have the best combination of liquid helium and fabrication characteristics for these coil frame applications.

Dewar Design

The complete prototype levitation magnet design is outlined in Fig. 5(i) and 5(ii). Features specific to the dewar design include:

- separate 35 litre liquid helium reservoir with integrated heat exchanger
- single liquid nitrogen cooled thermal shield (aluminum)
- fixed vapor cooled current leads
- folded column structural supports of glass and carbon fibre composites.
- ribbed aluminum alloy outer hull.

A summary of the principal results of the levitation magnet design is indicated in Table 2, where a comparison is made with the original design goals. It is clear that all of the prototype magnet specifications are within the design guidelines except the overall weight. Reductions in magnet weight are possible with the following measures:

a) reduction in reservoir capacity below

35 litres;

b) integration of the liquid helium reservoir and the coil frame within a single dewar envelope;

c) reduction in Cu:NbTi ratio below 2:1;

d) use of aluminum stabilized NbTi wire.

Some reduction in heat load follows from implementing a) and b). More advanced designs will consider these refinements, as well as minimization of the coil-to-dewar envelope separation.

CURRENT ACTIVITIES AND FUTURE PLANS

The superconducting magnet design study has identified a number of critical areas in magnet development. Foremost among these is the technology for coil fabrication using epoxy impregnation to produce coils with minimum training behaviour. With TDC support, a program has been initiated at CTF Systems with the goal of developing fabrication and test facilities suitable for lightweight, epoxy impregnated superconducting solenoid and racetrack magnets. Initial results of this program are promising, and impregnation and fabrication procedures have been established using copper wire coils. These epoxy impregnation methods will be applied to a number of test superconducting coils and their quenching characteristics will be studied.

Several changes are currently being analyzed in an evolution of the Canadian system design. These include relocation of the guideway aluminum strips in order to provide electrodynamic suspension through interaction with the on-board LSM coils, thus eliminating the separate levitation magnets. This relocation will be accomplished without significant alteration of the present box-shaped guideway geometry. The merits of this approach include:

- simplicity of magnet configuration
- reduced vehicle cross-section and hence improved specific energy consumption
- reduced on-board refrigeration, on-board power and weight requirements.

Maglev transportation systems are attracting worldwide attention, and both low and high speed modes are being considered by transportation planners. As an example of Canadian participation in these activities, researchers from CIGGT and NRC are conducting an assessment of both the EDS and EMS Maglev technologies for a high speed link connecting Los Angeles and Las Vegas.

CONCLUSIONS

This paper has presented an overview of the current status, activities, and future plans of the Canadian Maglev program. While this program cannot claim the large scale hardware developments so impressively demonstrated in Japan and in the Federal Republic of Germany, Canadian research has led to the definition, refinement and economic evaluation of a Maglev system appropriate for Canadian corridor applications. In addition, progress has been made towards establishing within Canadian industry, fabrication and test facilities for superconducting magnets and associated cryogenics technology.

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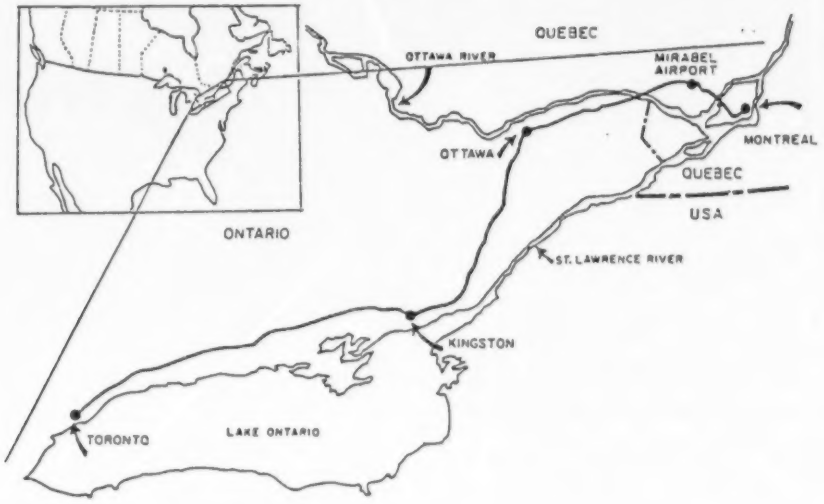

Fig.1 The Toronto-Montreal routing for the 450 km/hr Maglev system.

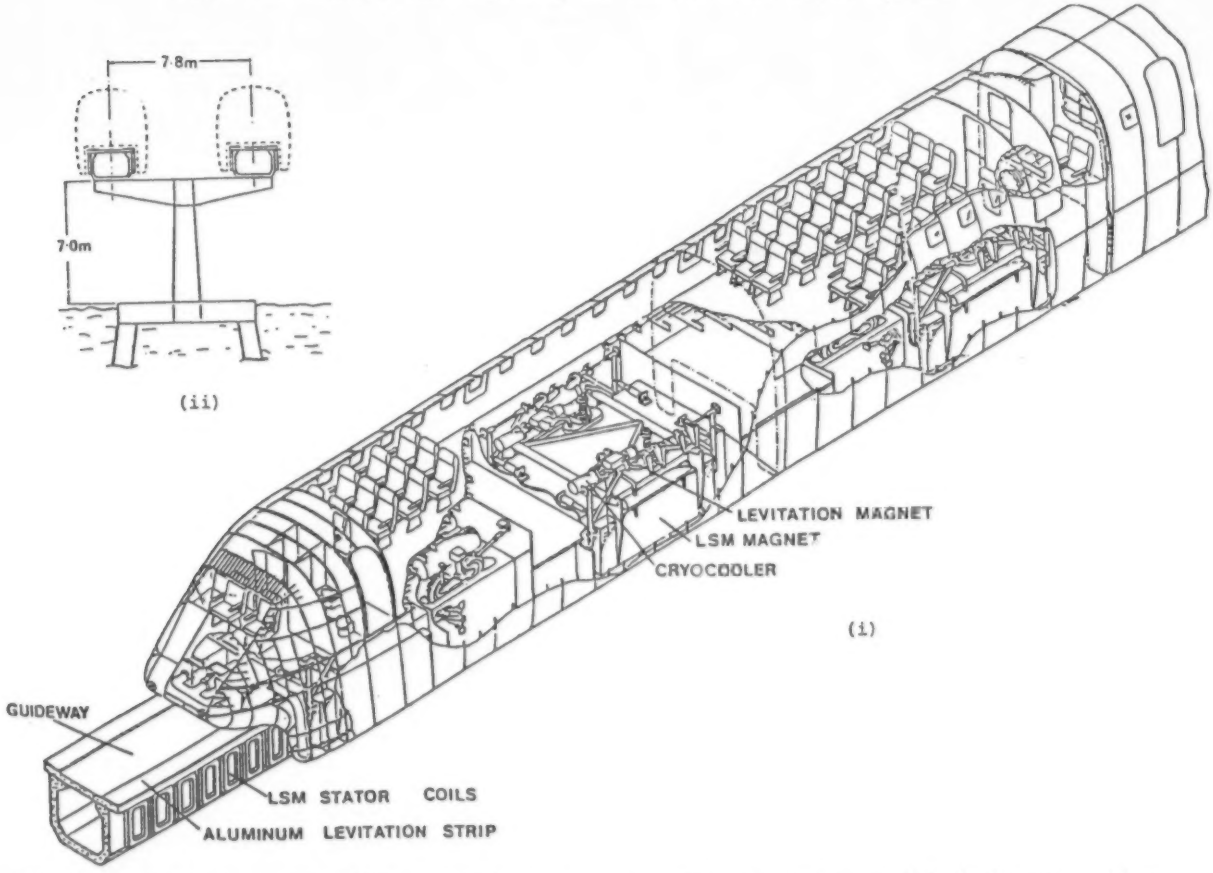

Fig. 2 The updated two-car Maglev system design (i) isometric of single car (ii) dual track guideway.

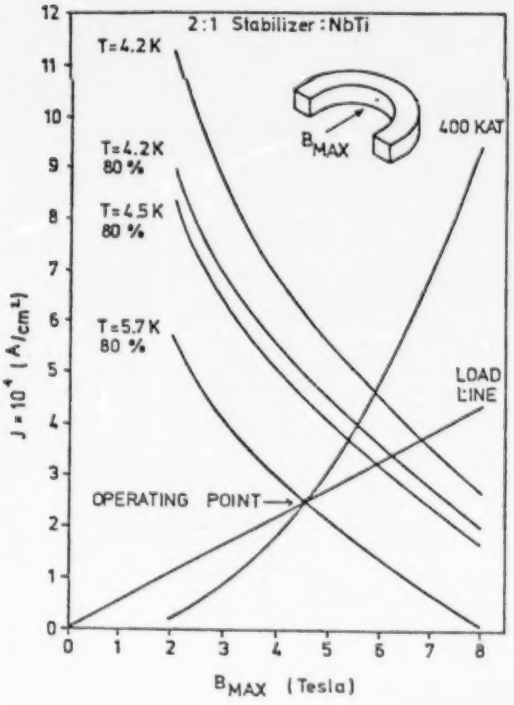

Fig. 3 Current density versus field and temperature for square section coils of mean radius 0.15m.

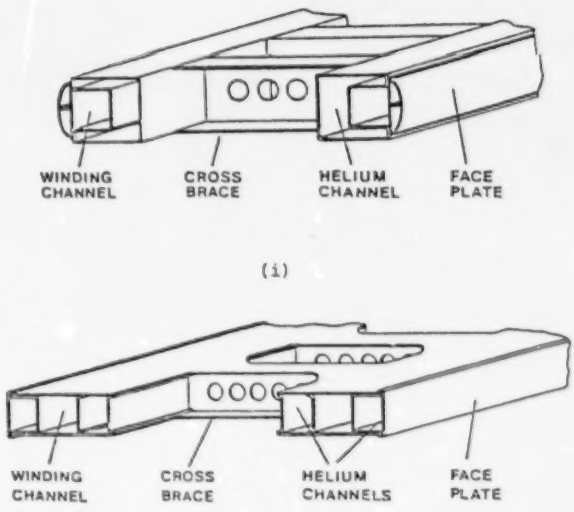

Fig. 4 Integrated coil frame and helium channel designs for the levitation magnet. In (i), the coil is cooled on 3 sides and in (ii), the cooling is reduced to 2 sides. The winding channel section has dimensions 4cm x 4cm.

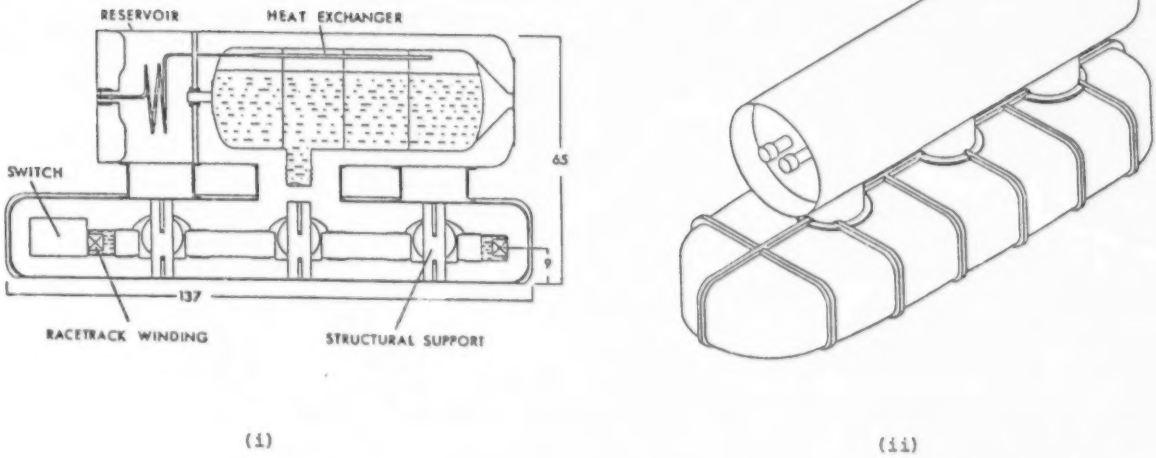

Fig. 5 Prototype levitation magnet (i) section view (ii) isometric view.